# ArgoNeuT Analysis Status

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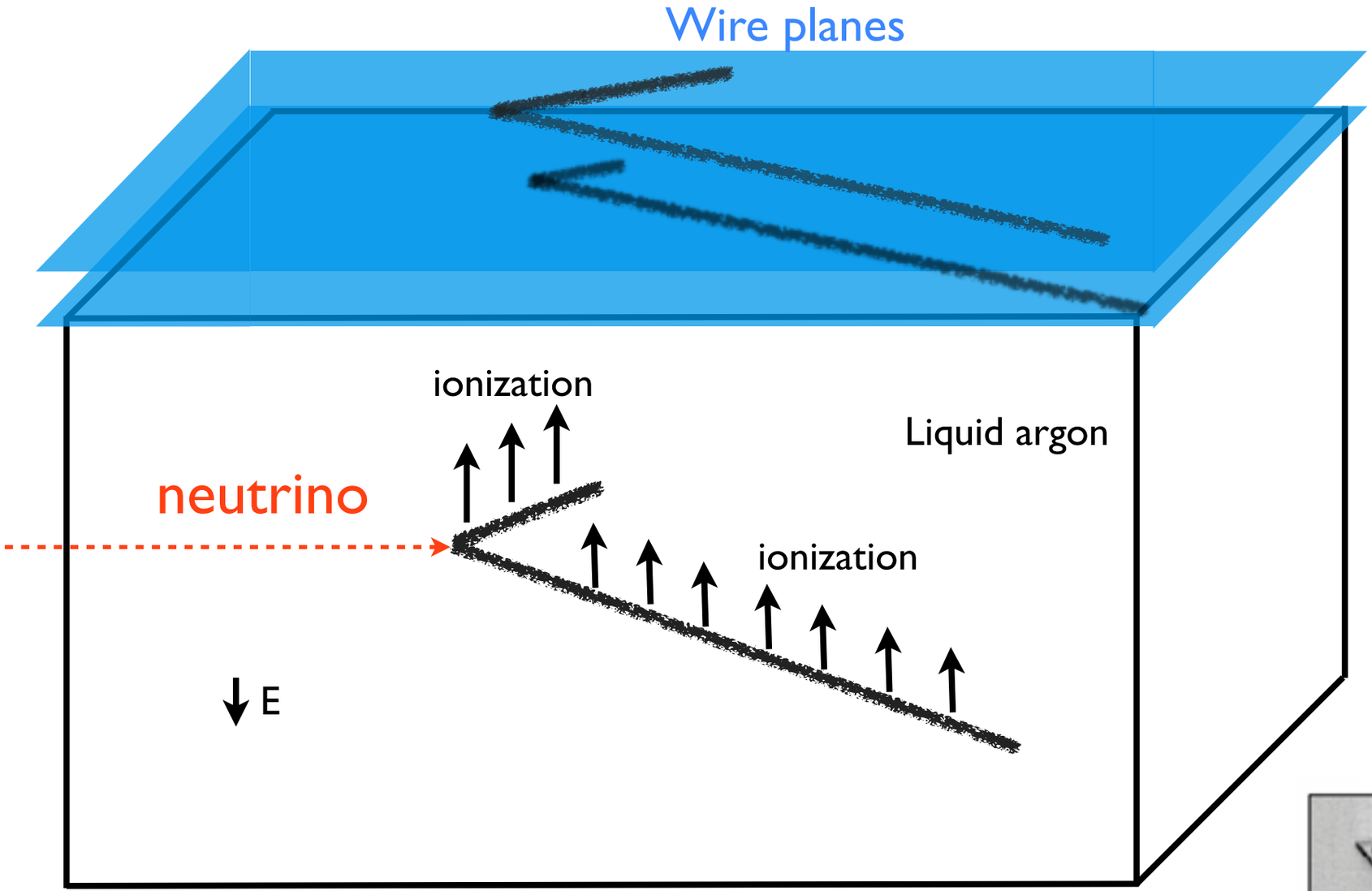
# Outline

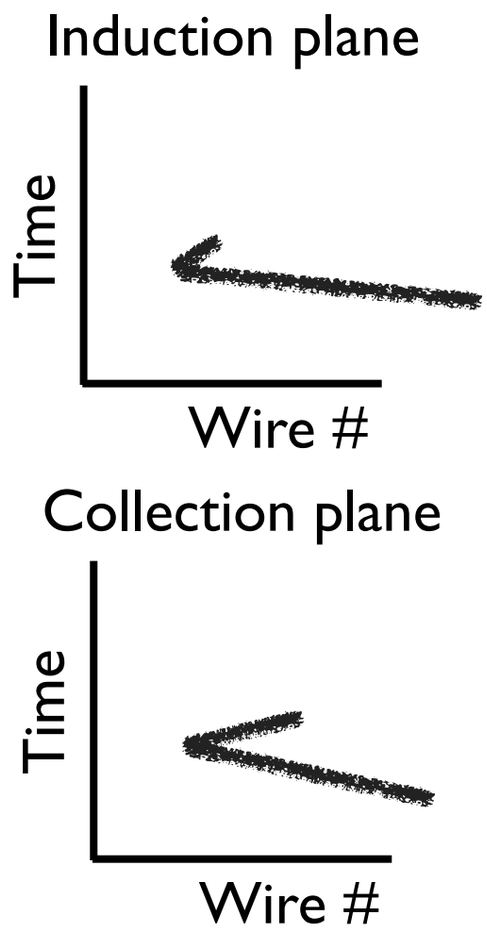
- The LArTPC concept and ArgoNeuT
- The physics run.
- What can ArgoNeuT see?
- What can ArgoNeuT tell us about FSI and vertex activity in general?
- Reconstruction and analysis status

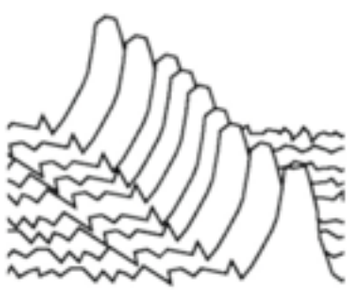
# A wish list for accelerator-based neutrino oscillation physics

- Beam:
  - Intense, pure beam w/ a smartly chosen L/E to coincide with the parameter space of ($\Delta m^2$, $\theta$) that you want to explore.
- Detector(s):
  - High resolution 3D imaging
  - Precise calorimetric reconstruction
  - Fully active
  - Homogeneous volume
  - Low energy threshold
  - Particle ID (background suppression)
  - Big (or scalable) and relatively inexpensive

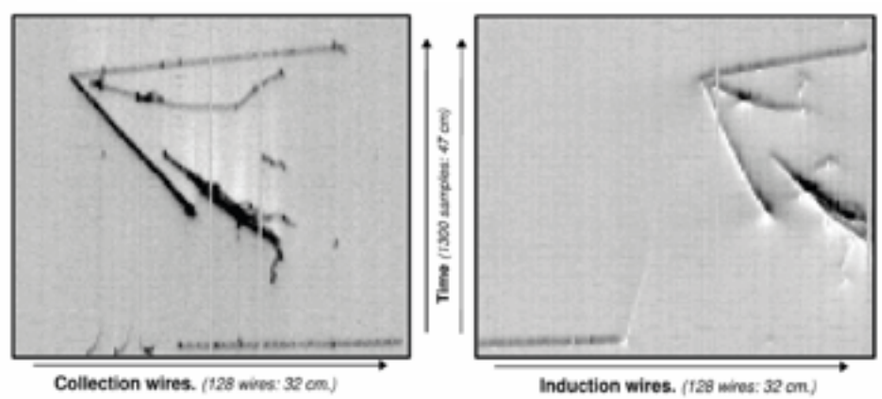
# The LArTPC concept



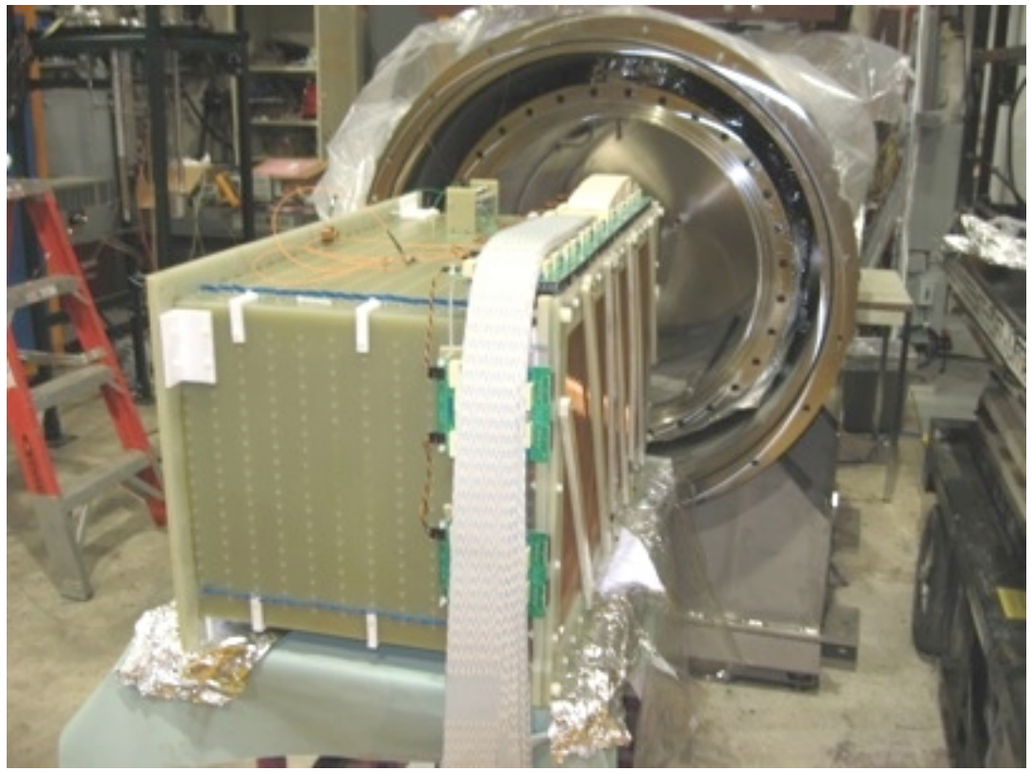
Wire pulses in time give the drift coordinate of the track




ICARUS 50 L in WANF neutrino beam

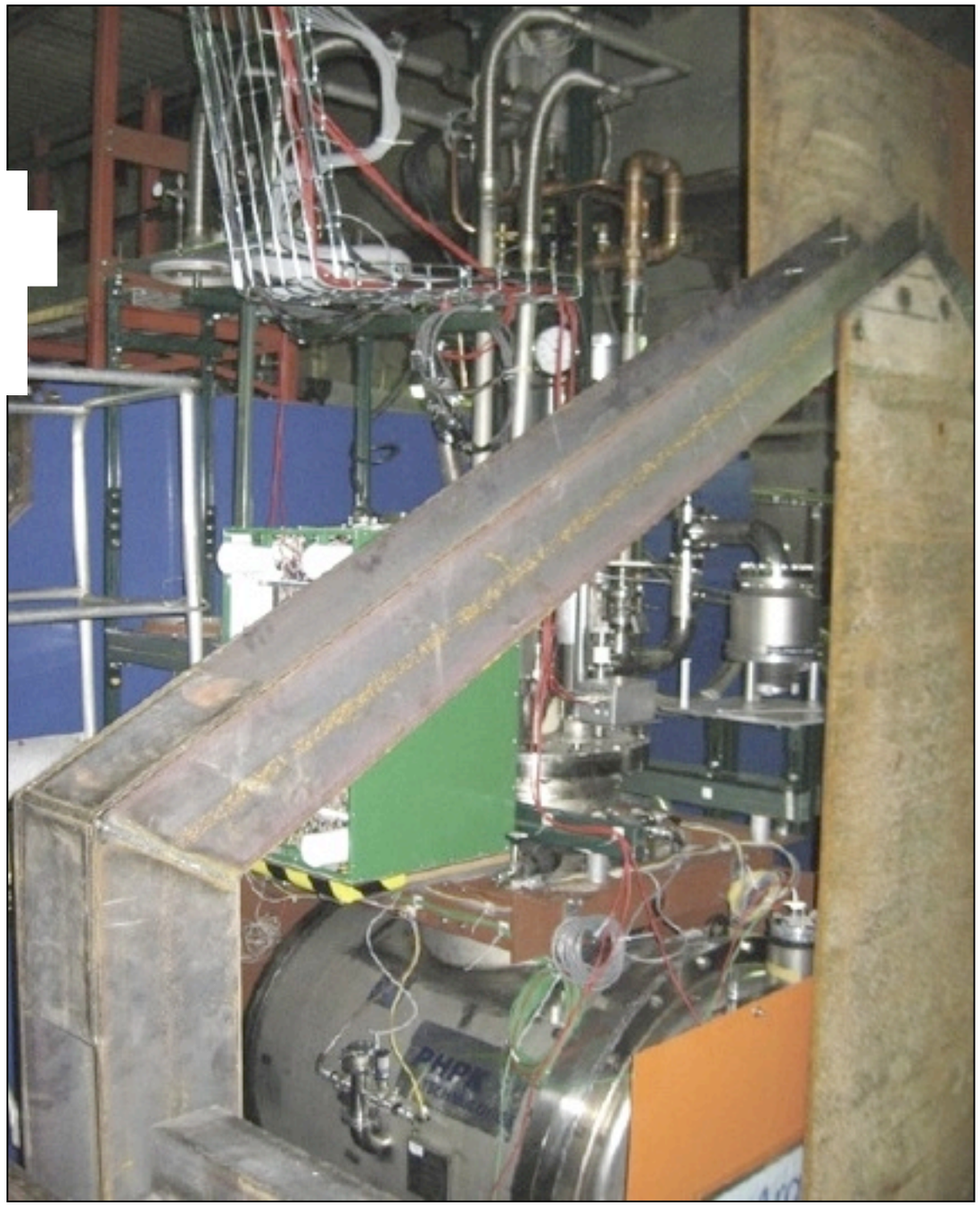
induction plane + collection plane + time = 3D image of event (w/ calorimetric info)

# ArgoNeuT TPC and cryostat



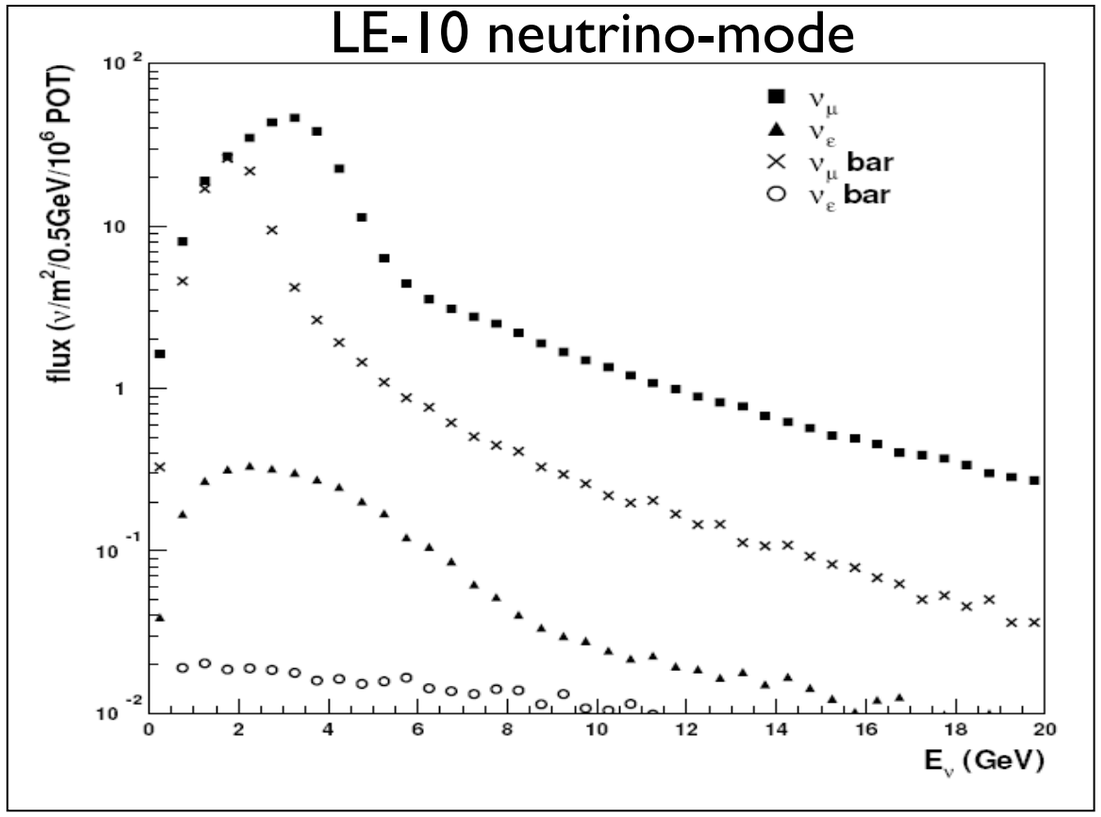
The TPC, about to enter the inner cryostat

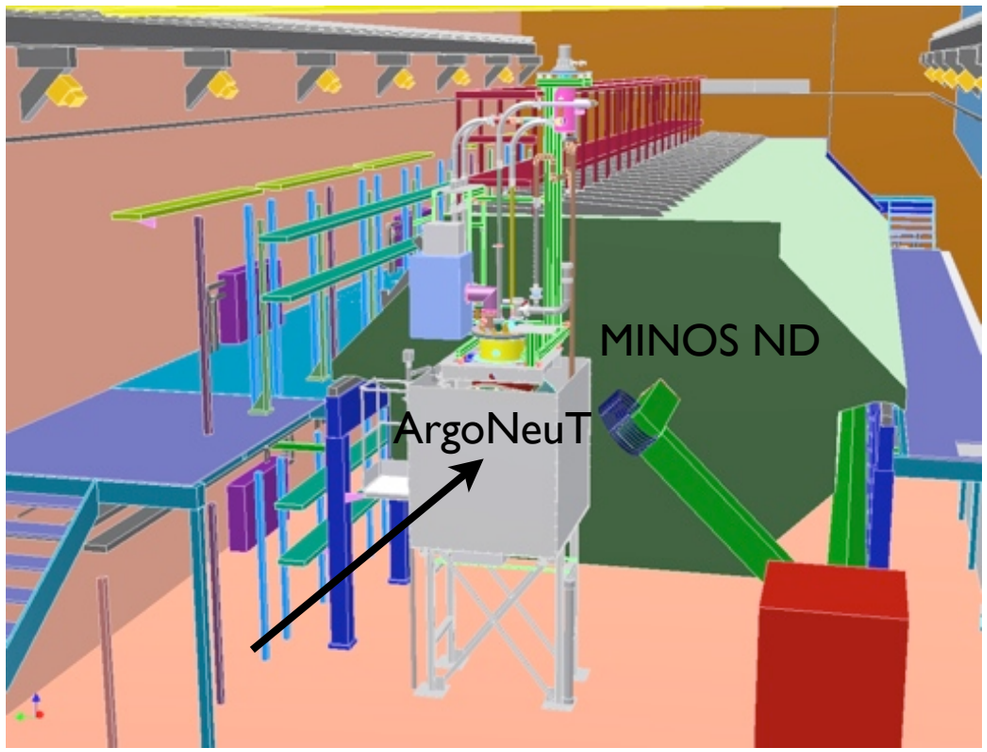
| | |
|---|---|
| Cryostat Volume | 500 Liters |
| TPC Volume | 175 Liters |
| # Electronic Channels | 480 |
| Wire Pitch | 4 mm |
| Electronics Style (Temperature) | JFET (293 K) |
| Max. Drift Length (Time) | 0.5m (330μs) |
| Light Collection | None |

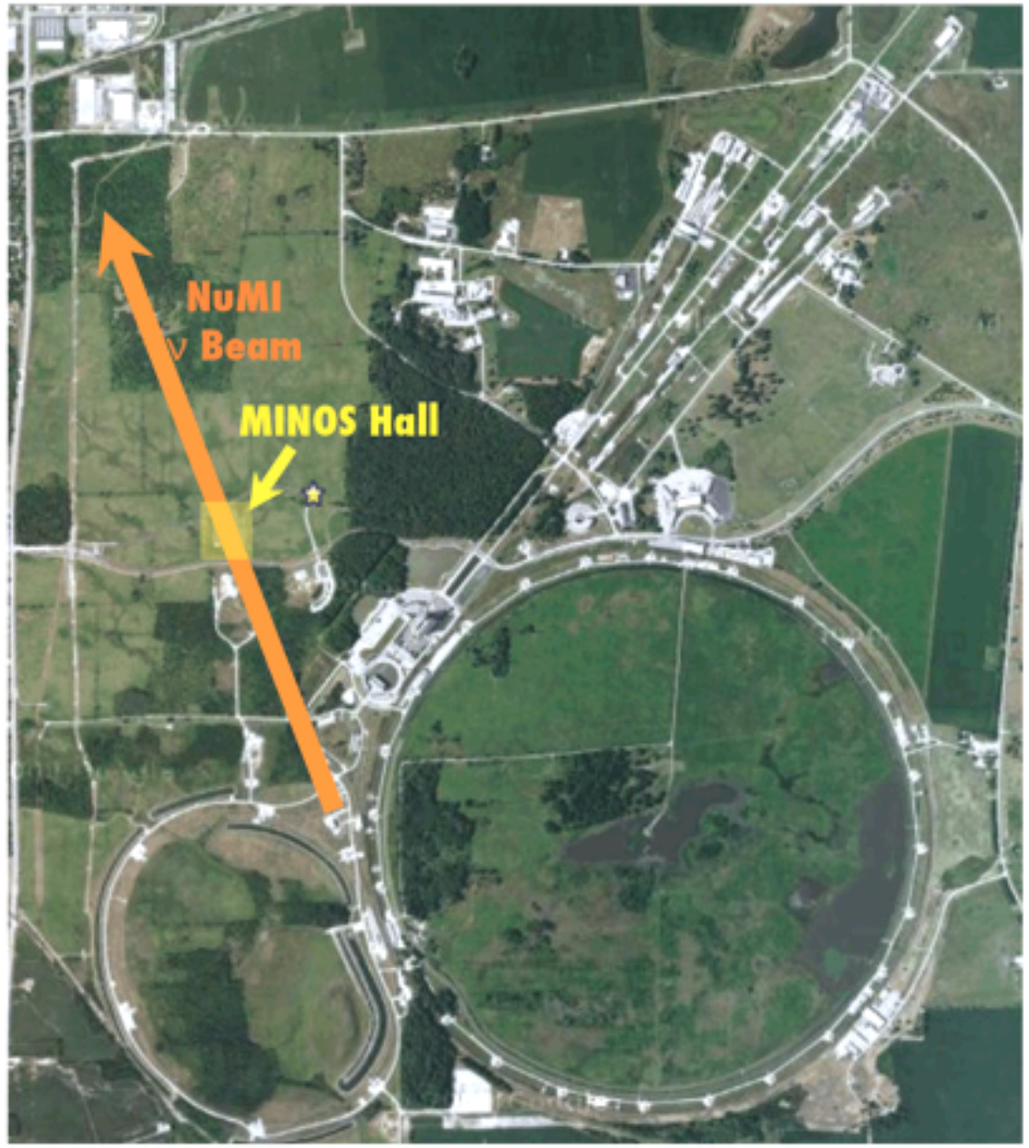


The fully-instrumented detector in the beamline

# ArgoNeuT in the NuMI beam

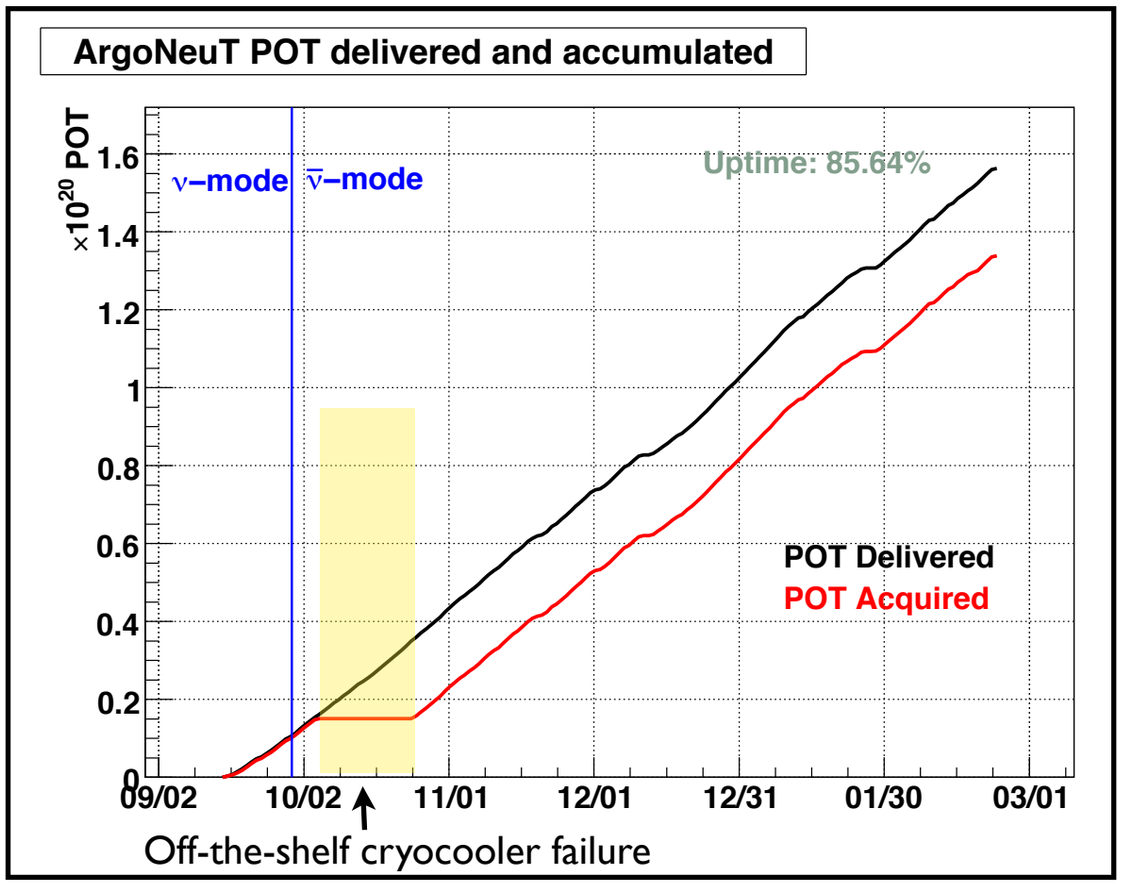



NuMI beamline at Fermilab

# ArgoNeuT's physics run



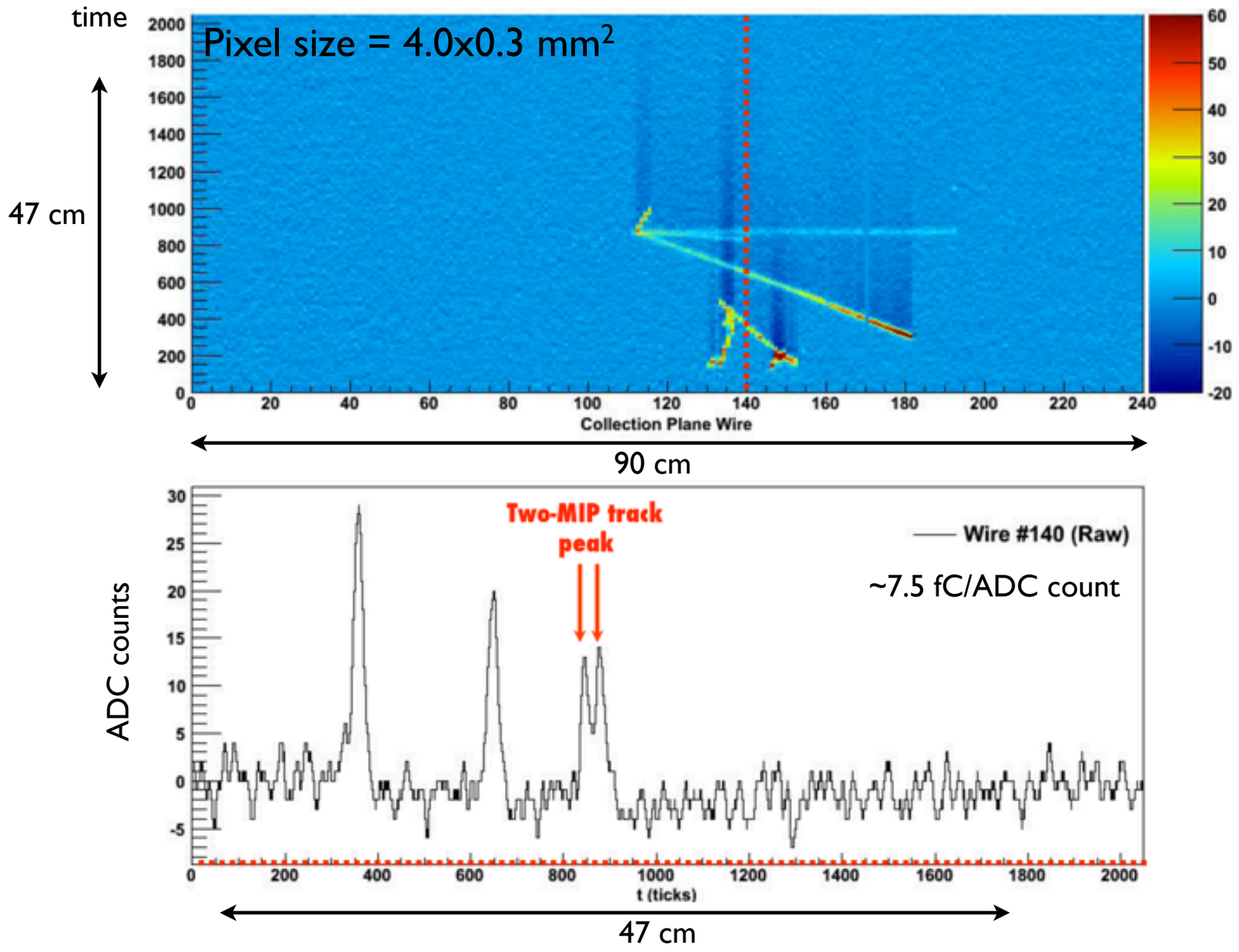

2 weeks in neutrino-mode, 4.5 months in anti-neutrino-mode

- ArgoNeuT (NSF/DOE) completed its phase I physics run, lasting from 9/14/2009-2/22/2010.
- Physics goals:
  - Measure charged-current absolute and differential cross sections in the 1-5 GeV range with high sensitivity to the products of FSI.
  - dE/dx particle separation (e.g. e/γ) capabilities of LArTPCs will be demonstrated.
  - Developing automated reconstruction techniques, to be used for ArgoNeuT and future LArTPCs.

| Reaction | #events in AV (~1.35E20 POT) |
|---|---|
| $\nu_\mu$ CC | ~6600 |
| $\overline{\nu}_\mu$ CC | ~4900 |
| $\nu_\mu$ CCQE | ~600 |
| $\nu_e$ CC | ~130 |

- Stable, shift-free operation for >5 months!
- The first 1000s of (anti-)neutrino LArTPC events collected in a low-energy (~3 GeV) neutrino beam ever!

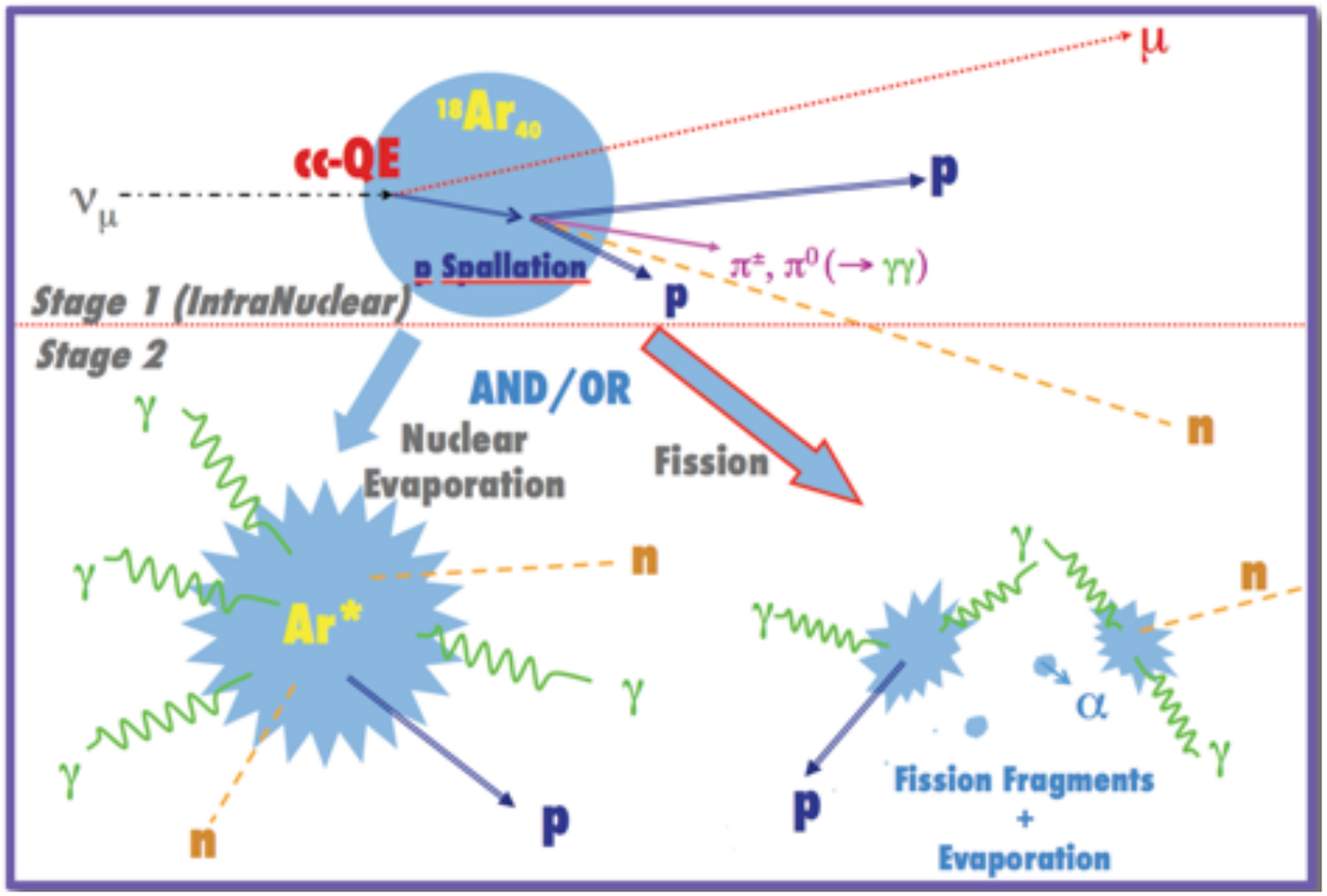
# How to read the event display?




- The actual wire pulses can be seen here in the "wire view".
- The color scale is indicative of the energy deposited along the track.

# CCQE interactions

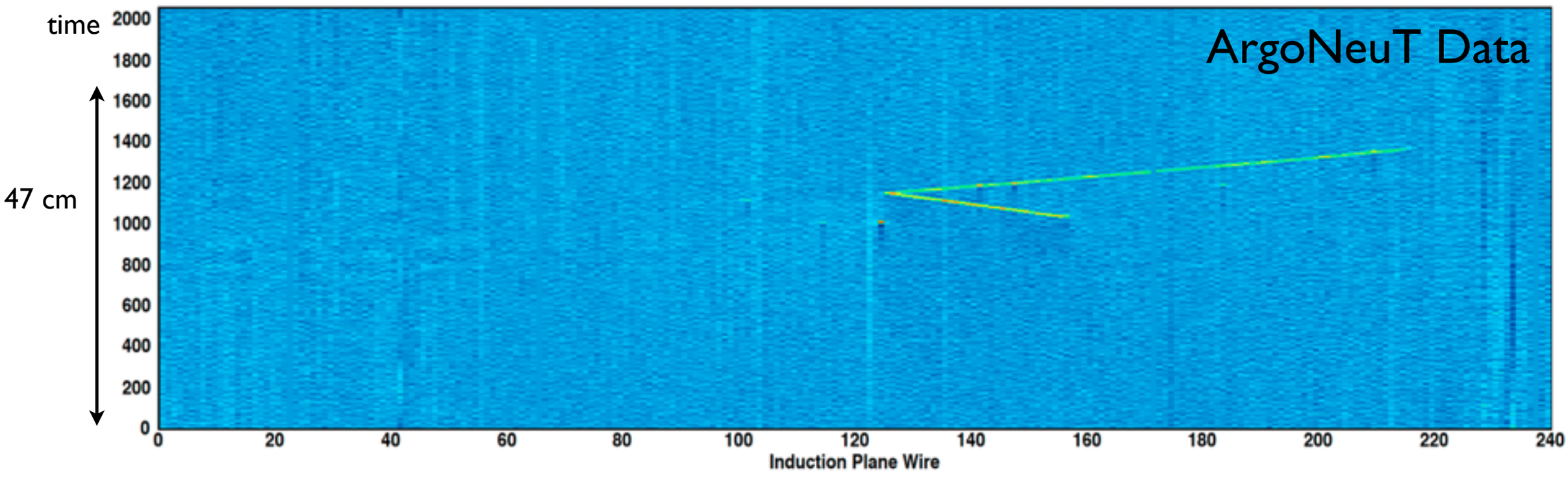
- What can ArgoNeuT really see with pixel size of 4.0x0.3 $mm^2$?
  - Well-resolved proton tracks as low as 50 MeV.
  - De-excitation photons.

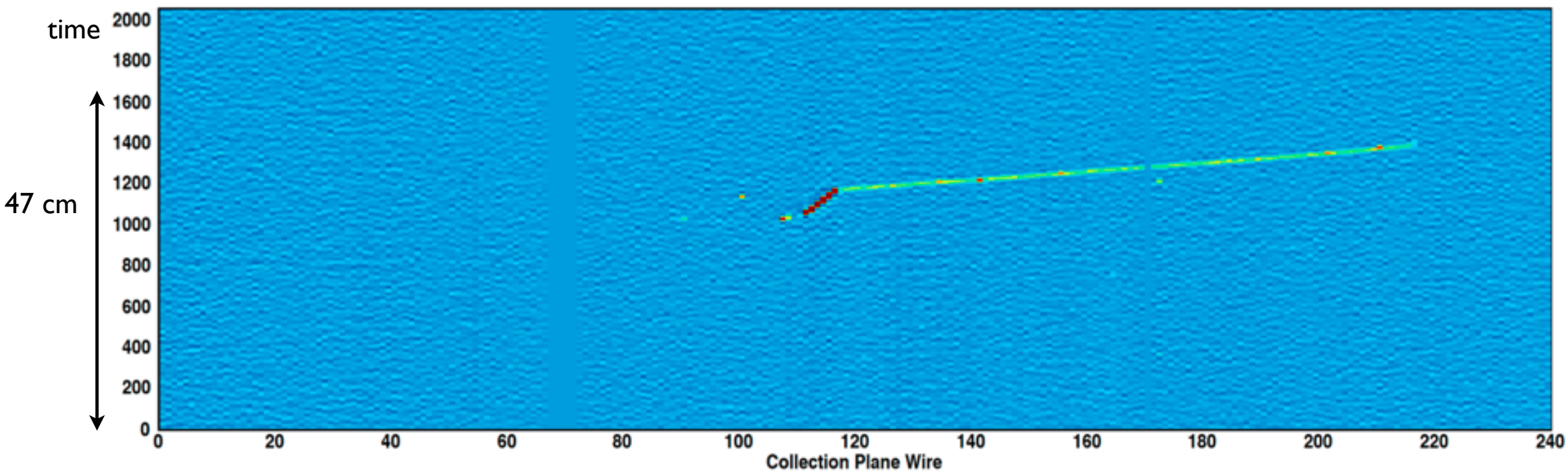



Let's take a look at some neutrino-mode events!

Low charge

High charge



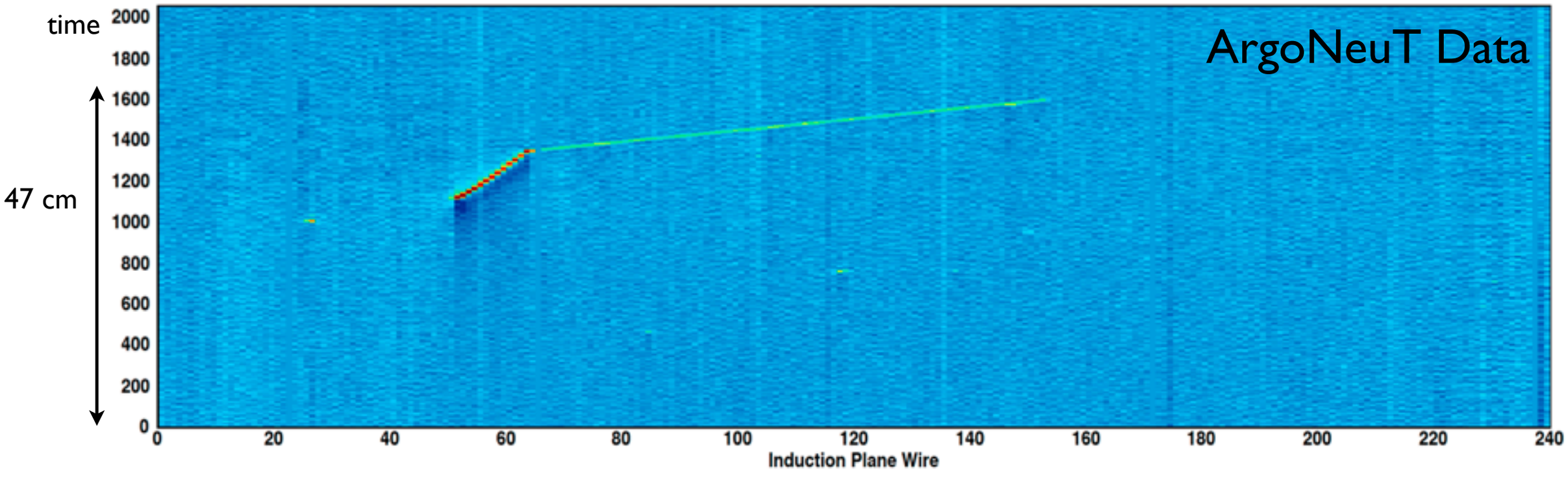



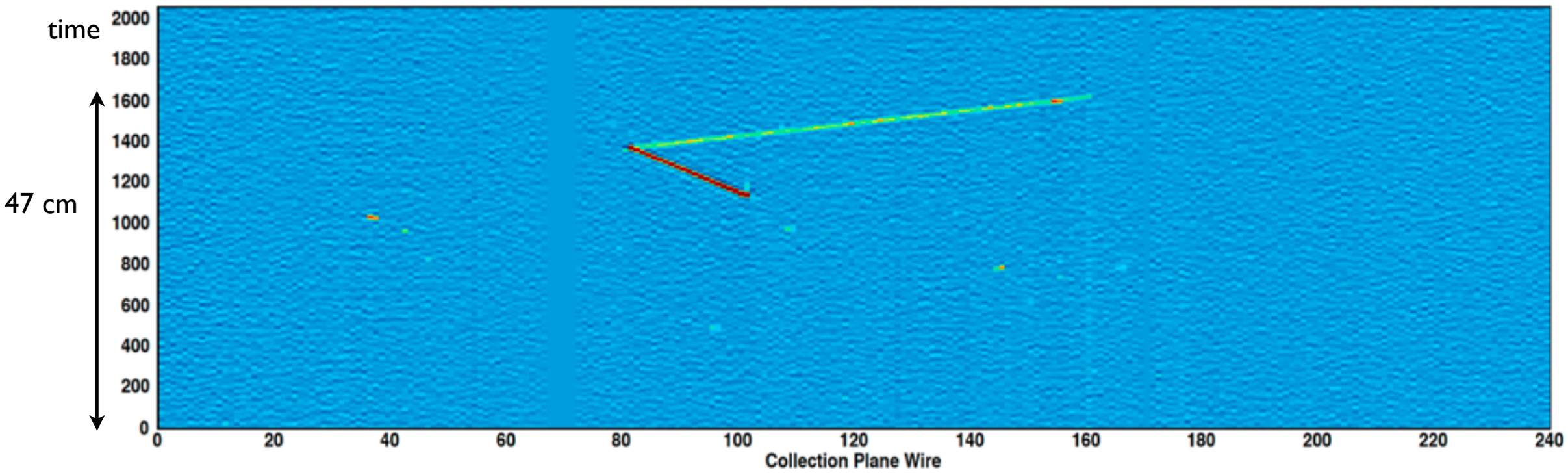

90 cm

10

Low charge

High charge

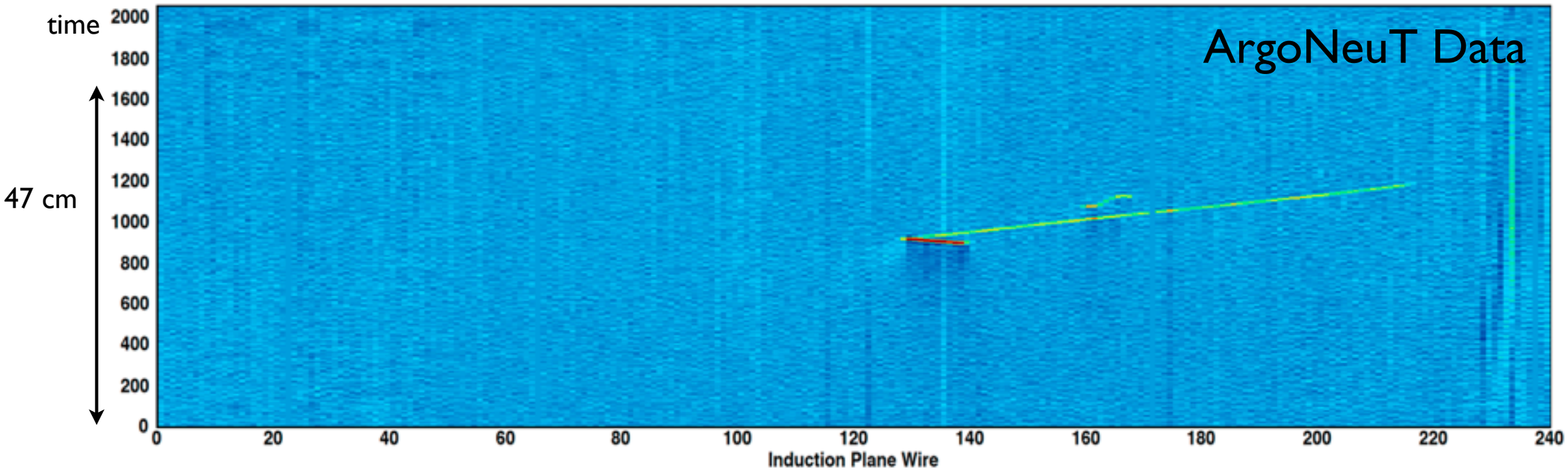


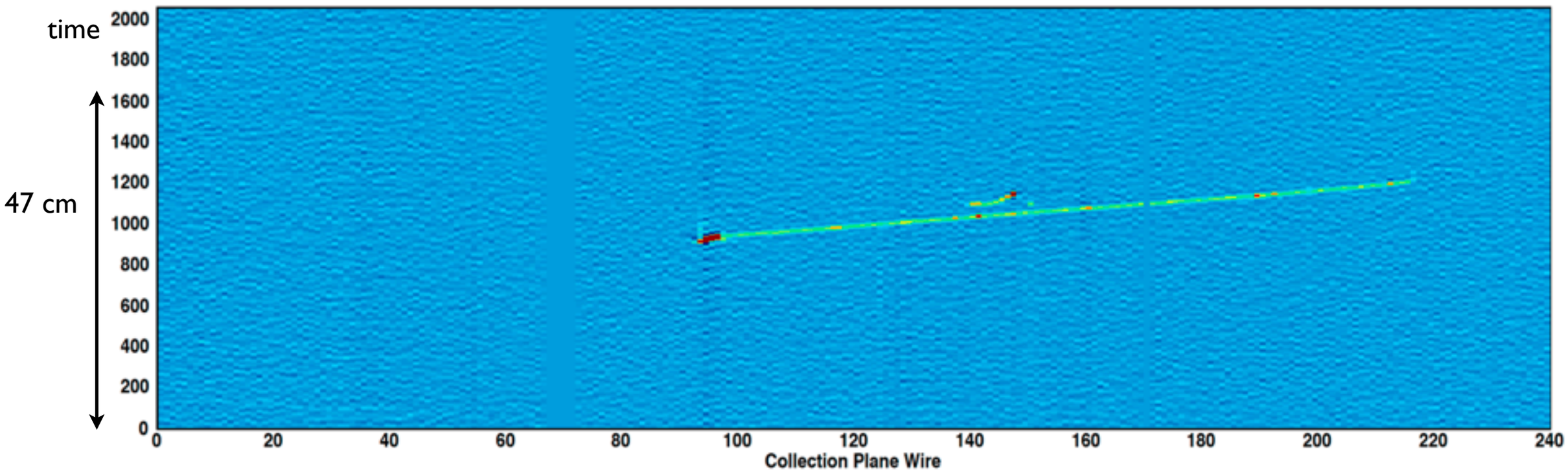




90 cm

Low charge

High charge



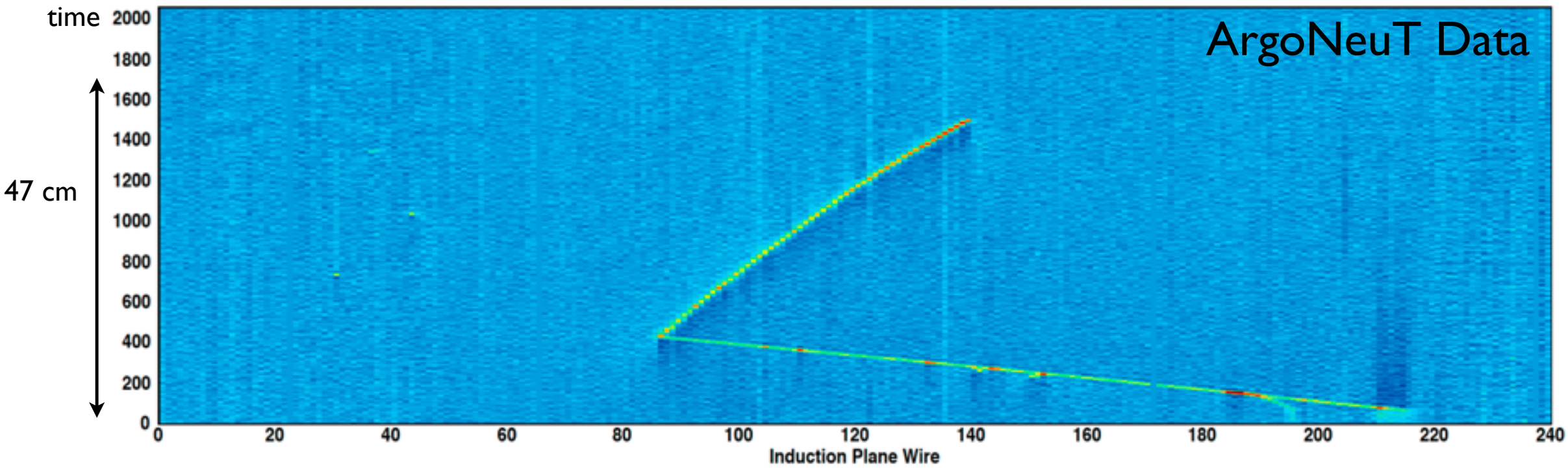



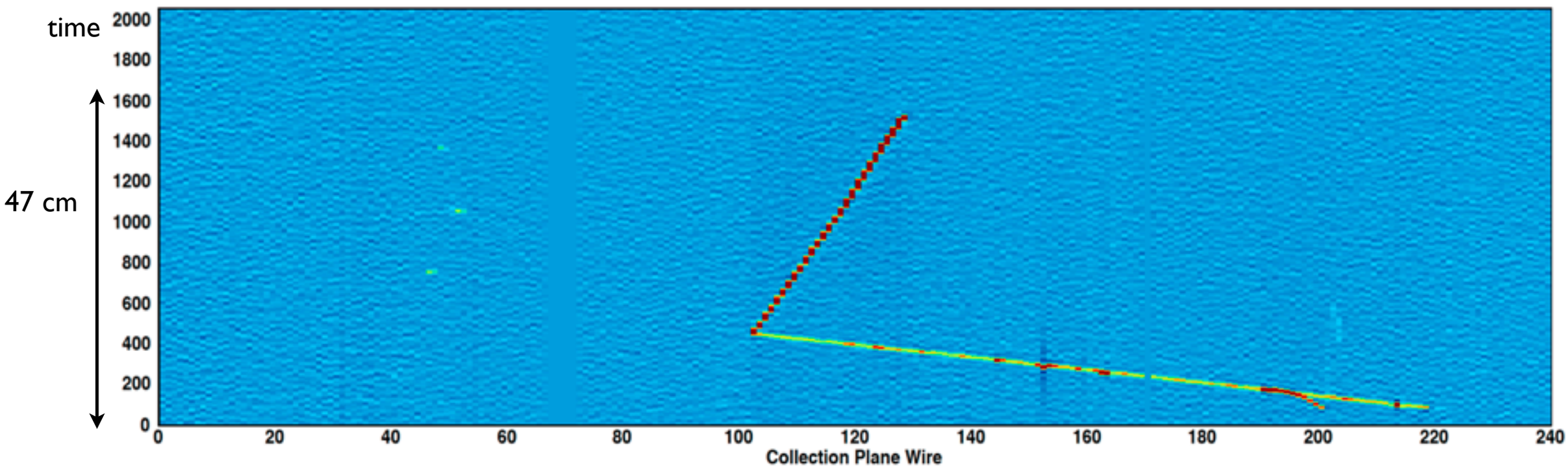

90 cm

12

Low charge

High charge

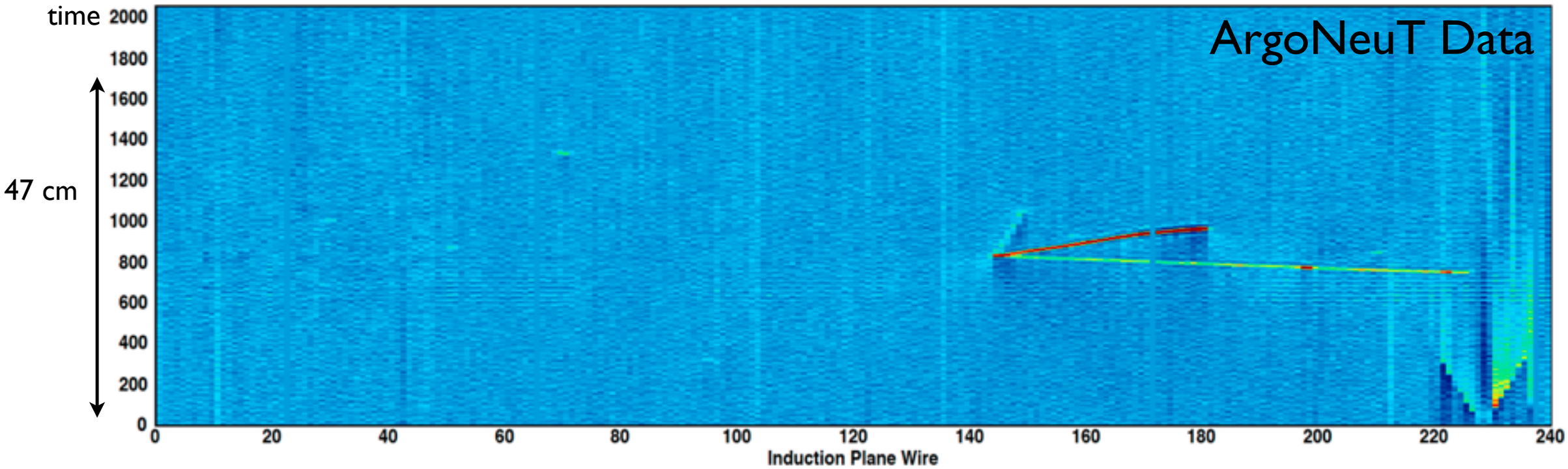


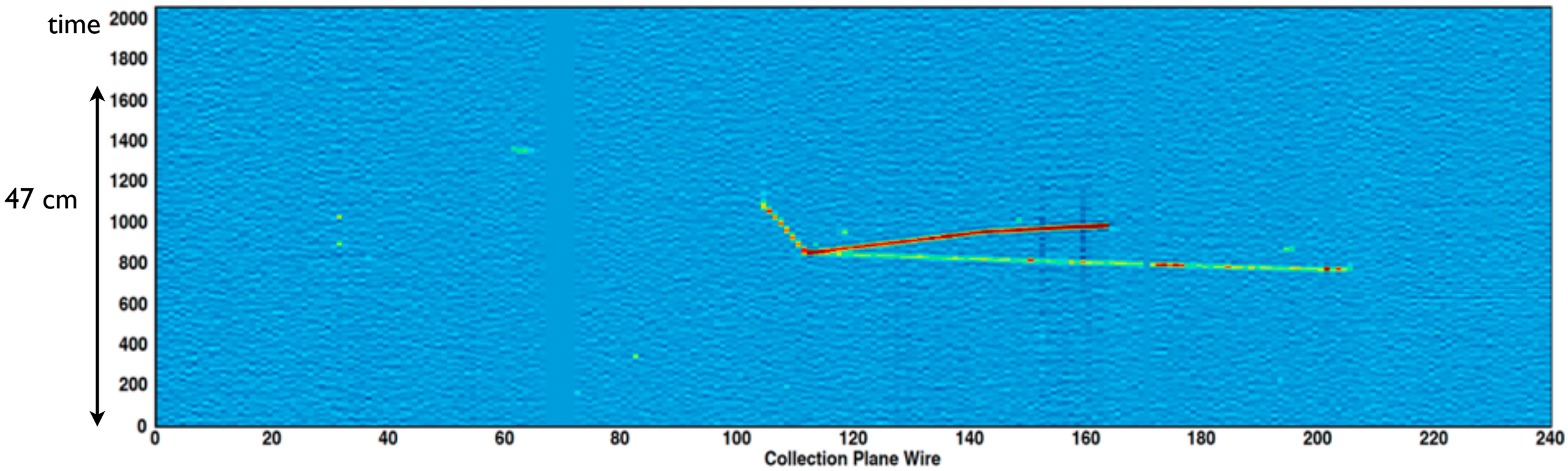




90 cm

Low charge

High charge

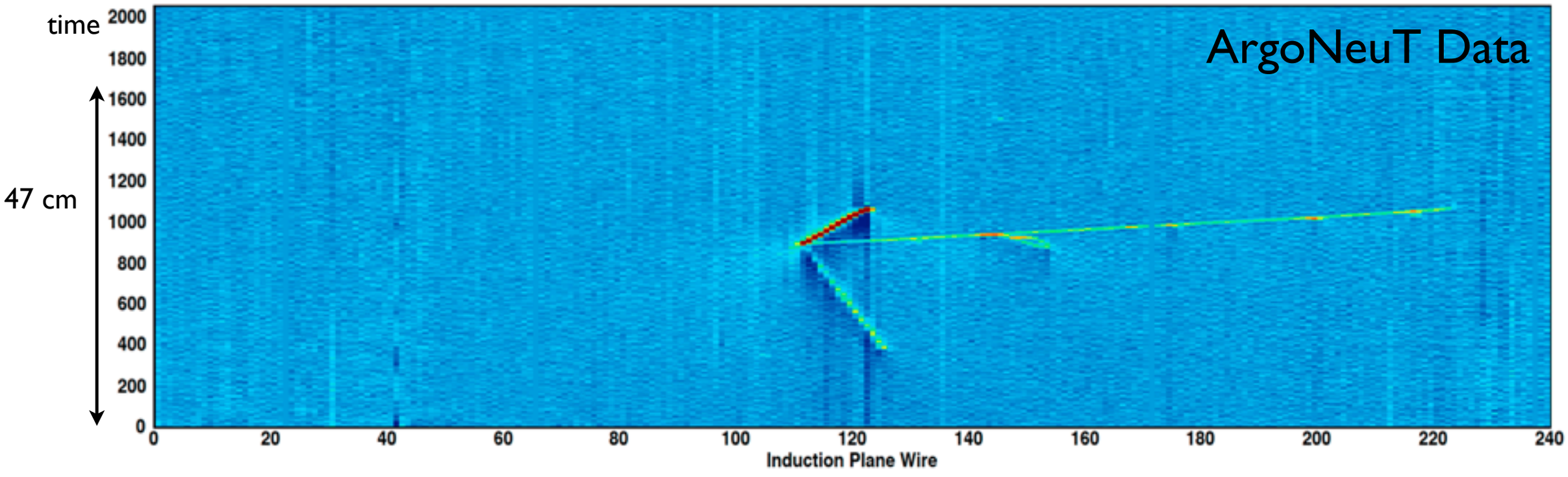


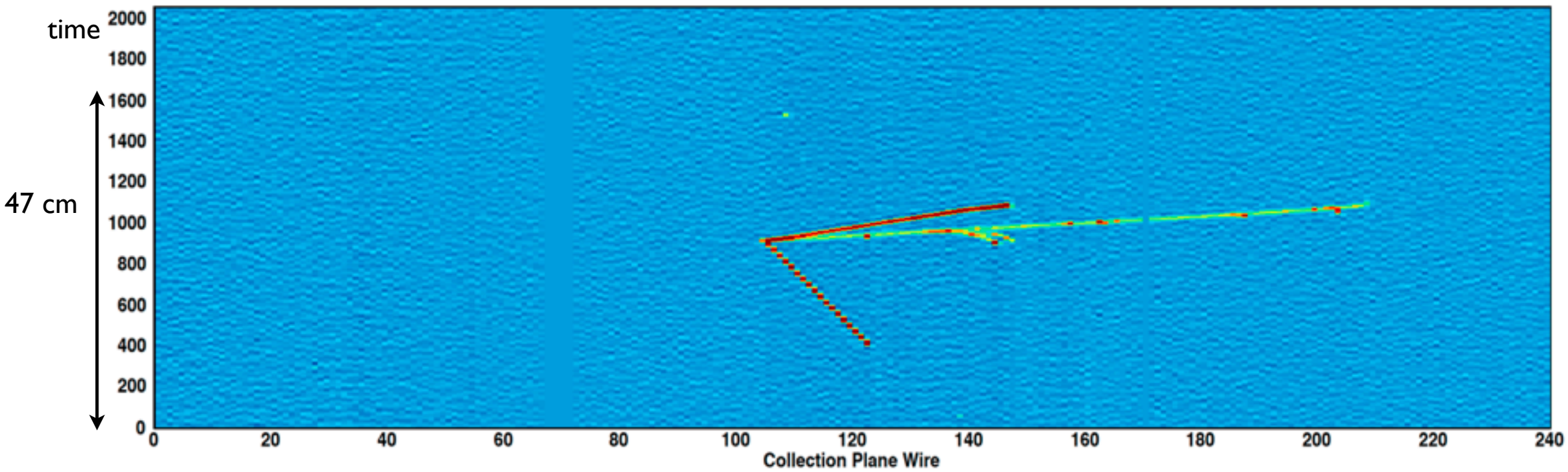




90 cm

Low charge

High charge

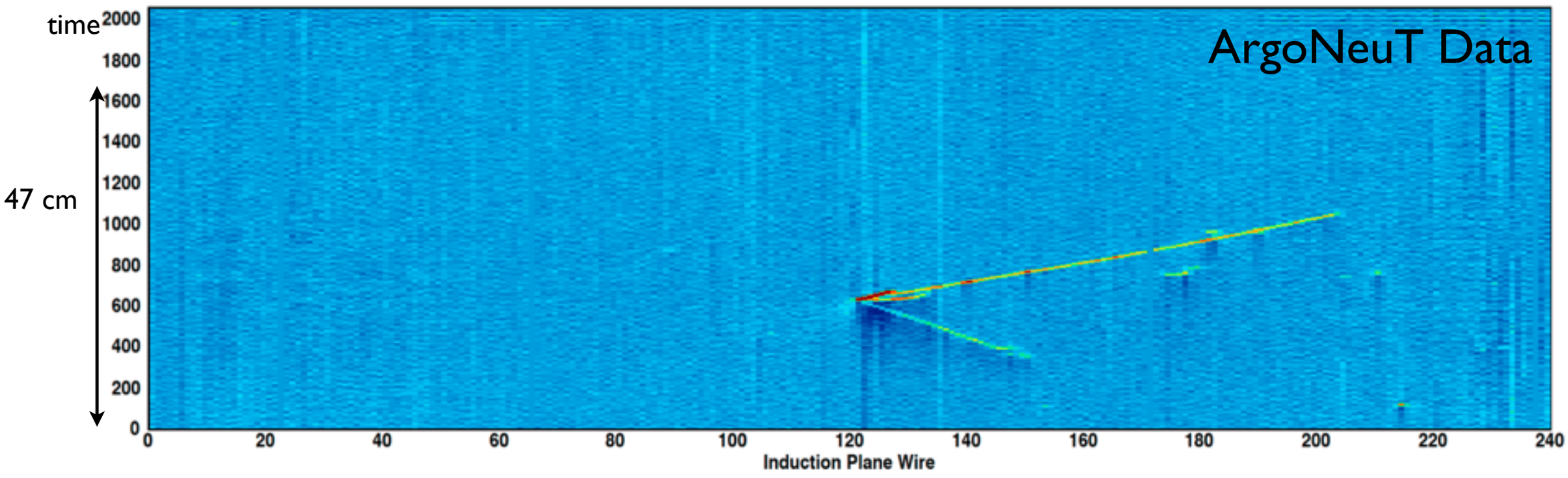


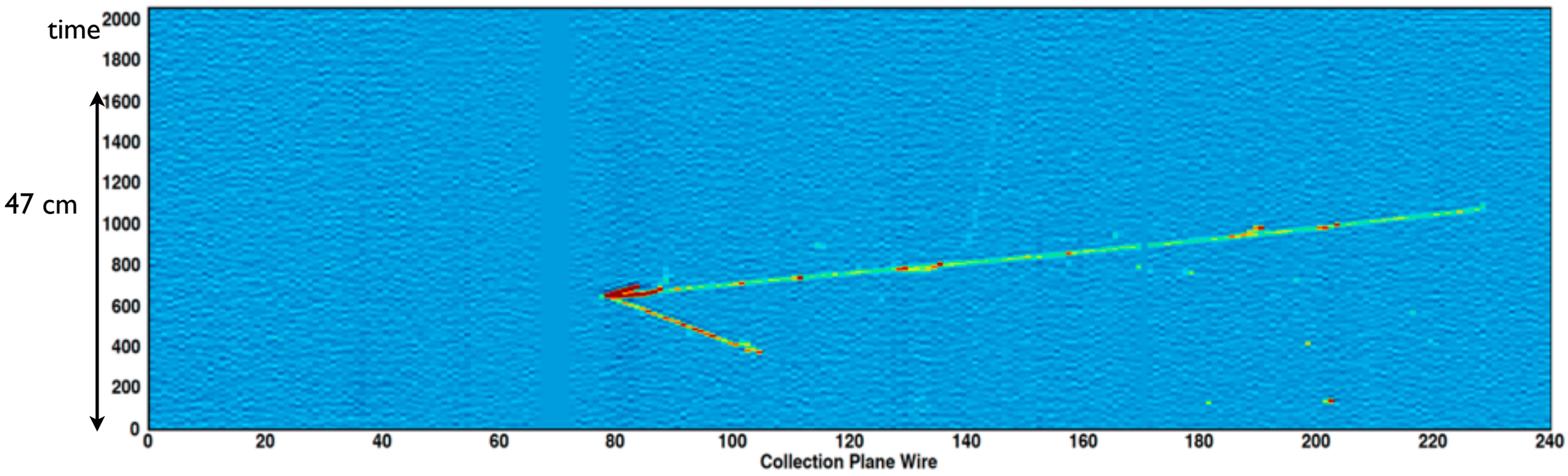




90 cm

Low charge

High charge

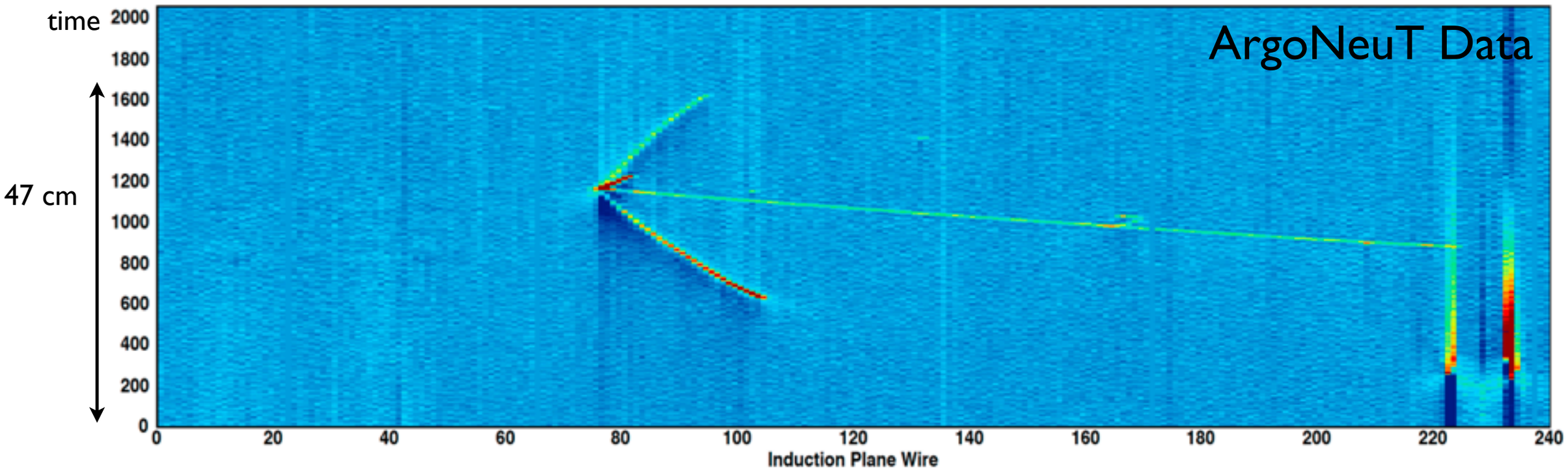


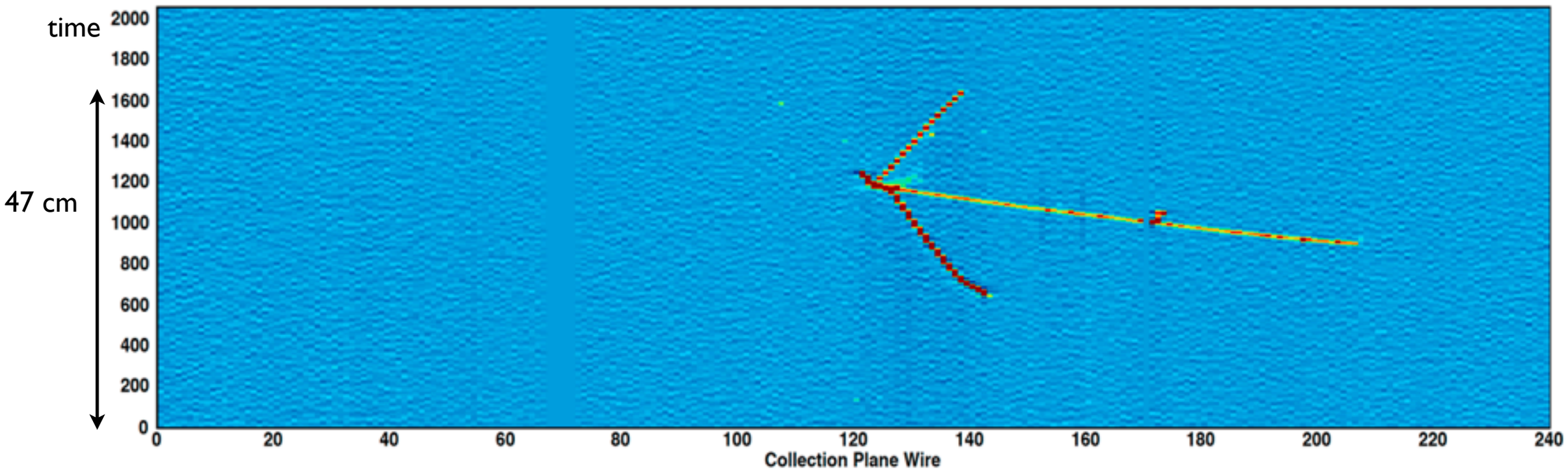




90 cm

Low charge

High charge

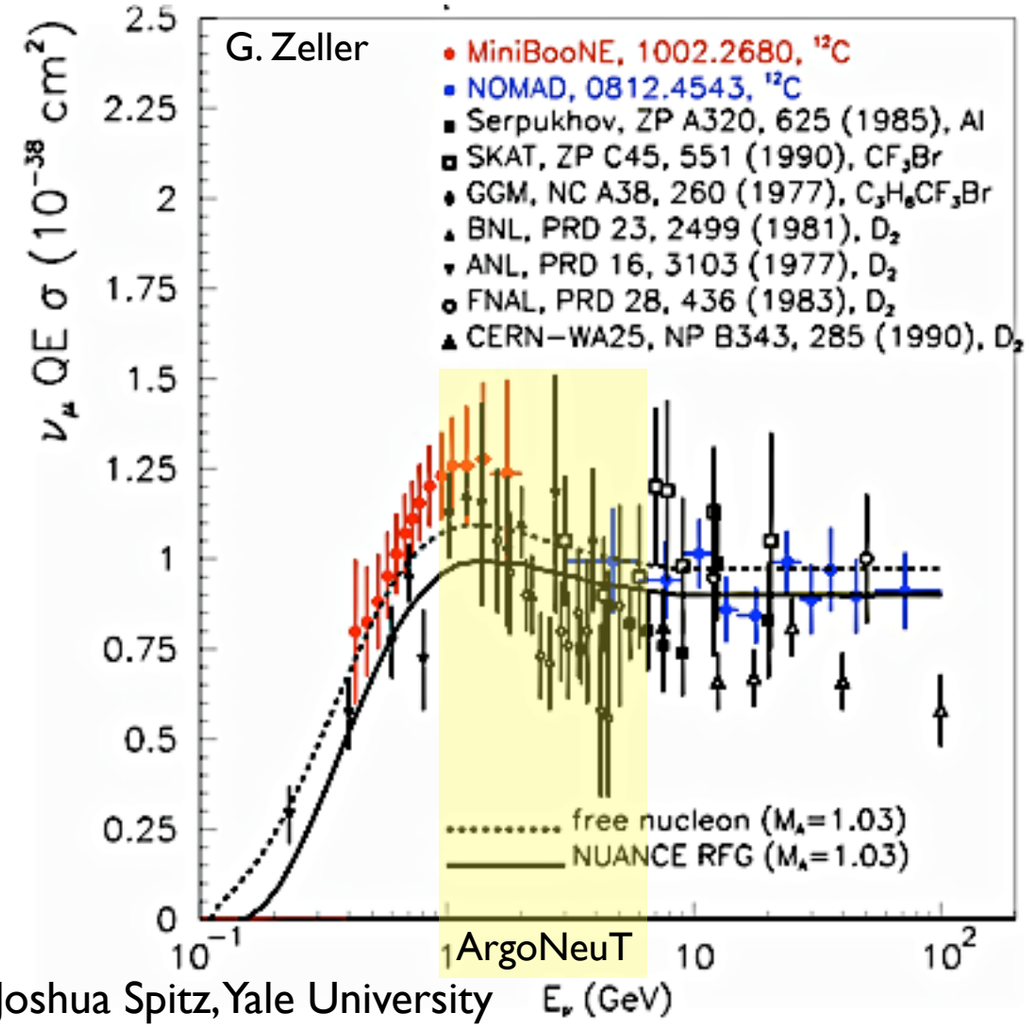


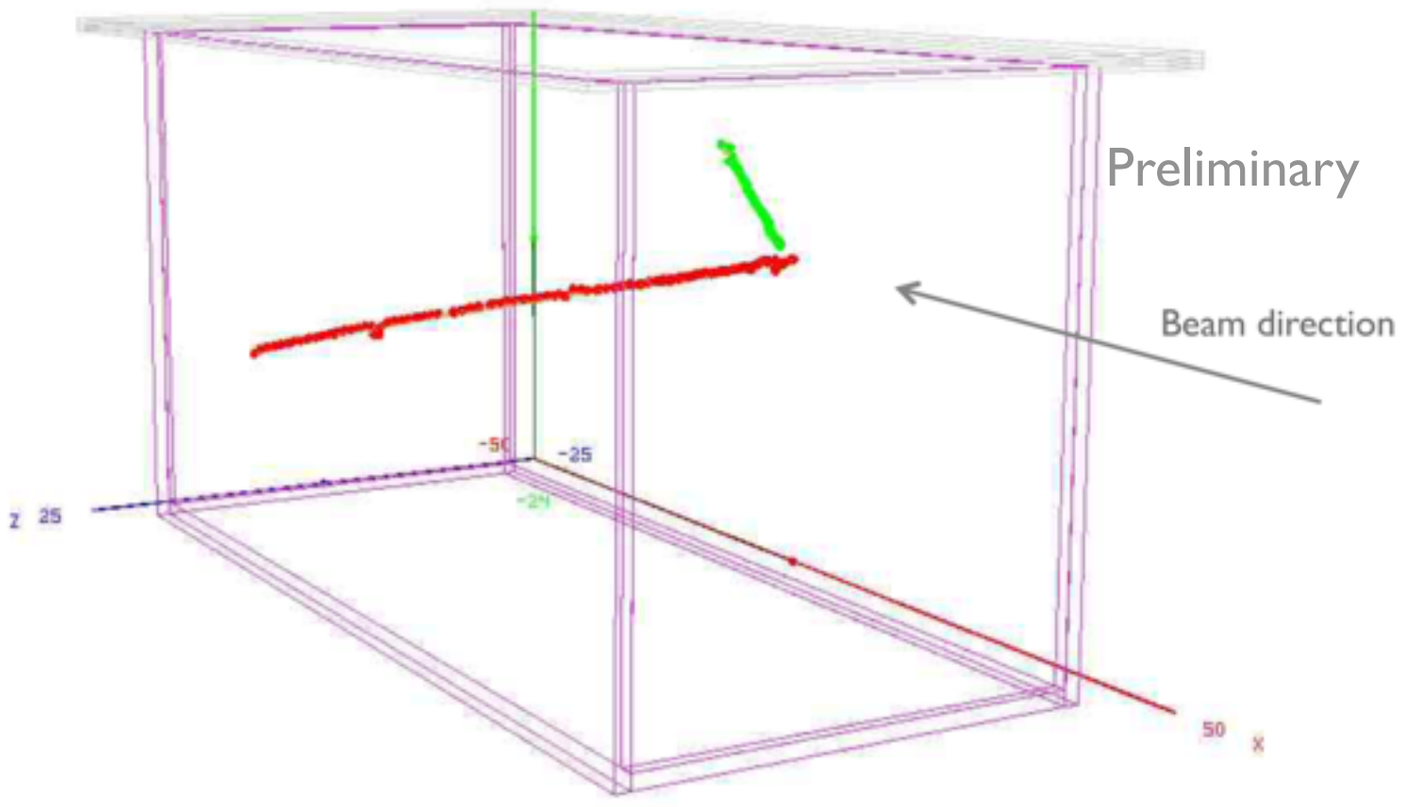

90 cm

# Addressing the CCQE puzzle

- The CCQE interaction is the "golden channel" for most GeV-scale neutrino oscillation experiments.
- However, the CCQE cross section uncertainty over most of the relevant energy range is large.For example, recent MiniBooNE and NOMAD (both $^{12}C$) CCQE cross section measurements disagree by up to 30% or more.
  - Both detectors are unable to fully resolve the "vertex activity" (protons) associated with CCQE events.
    - MiniBooNE's CCQE analysis is blind to protons.
    - NOMAD is blind to protons with energy less than ~300 MeV.
- With mm-scale resolution and 3D imaging, ArgoNeuT will analyze the vertex activity kinematics and measure differential kinematic and total cross sections for CCQE-like (anti-)neutrino events from ~1-5 GeV.

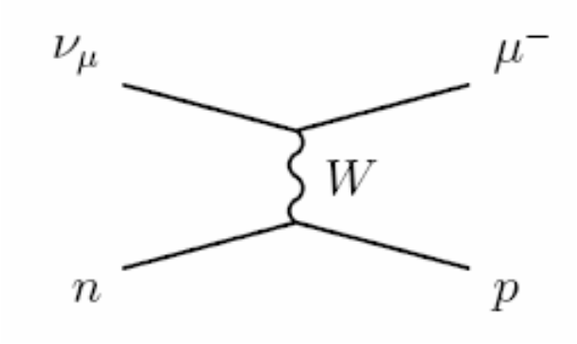



A CCQE-candidate event reconstructed in 3D

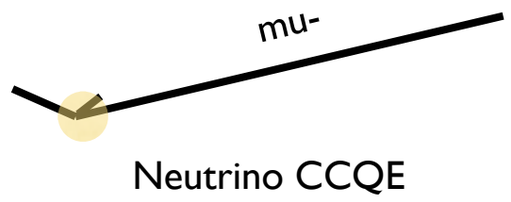


# Understanding vertex activity

- Not only is ArgoNeuT able to characterize vertex activity in CCQE-like events, it can also differentiate neutrinos from anti-neutrinos with the help of the MINOS near detector.
- Comparing neutrino and anti-neutrino CCQE-like events may provide some sensitivity to a possible multinucleon channel, involving 2p (2n) pre-FSI final states for neutrino (anti-neutrino) events.

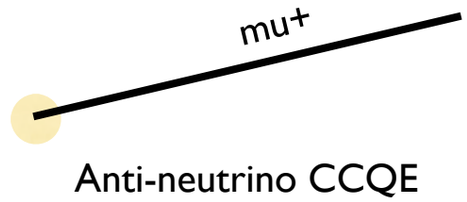



$\nu_\mu n \rightarrow \mu^- pp$

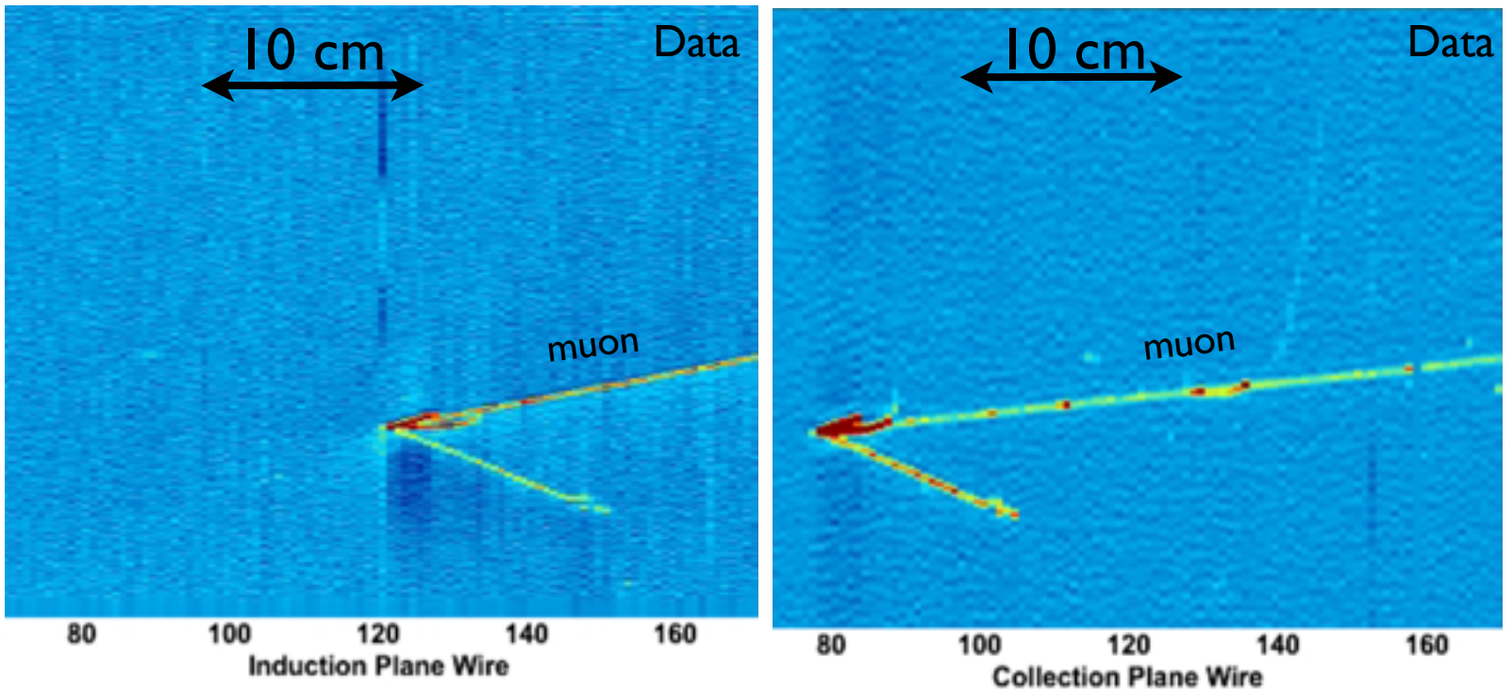



Neutrino CCQE

$\overline{\nu}_\mu p \rightarrow \mu^+ nn$




Anti-neutrino CCQE

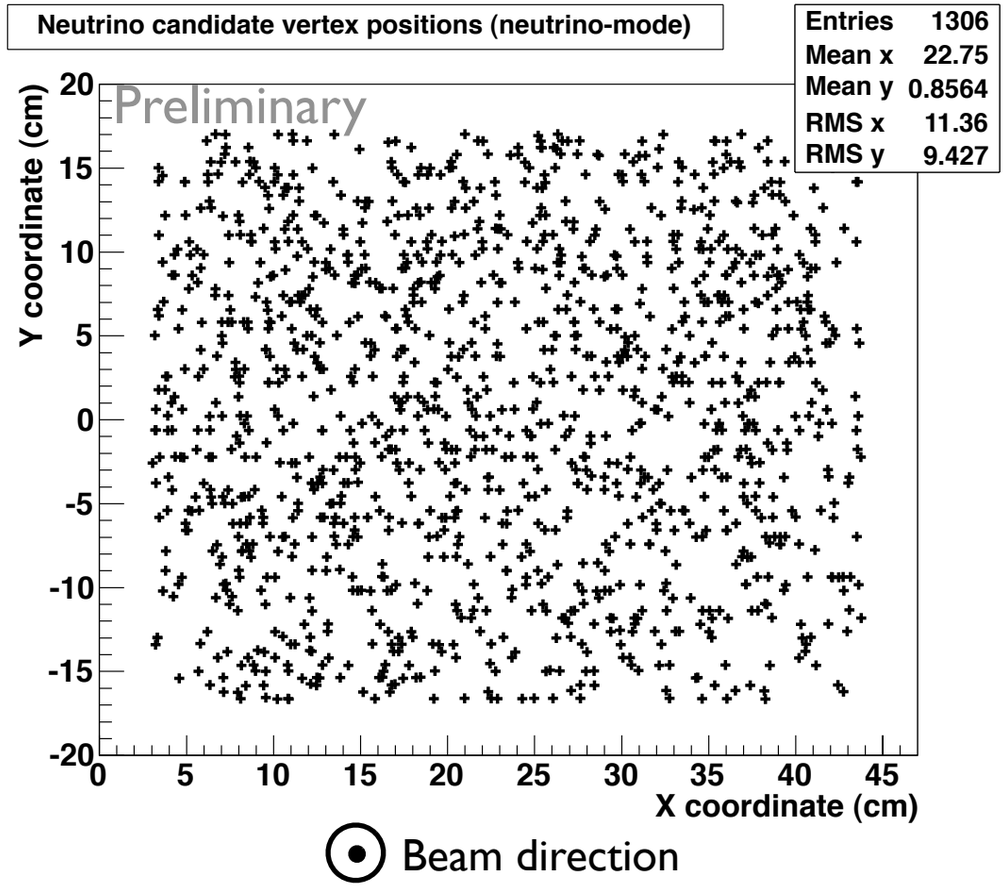



A zoomed-in view of a CCQE-like neutrino event with evidence of vertex activity

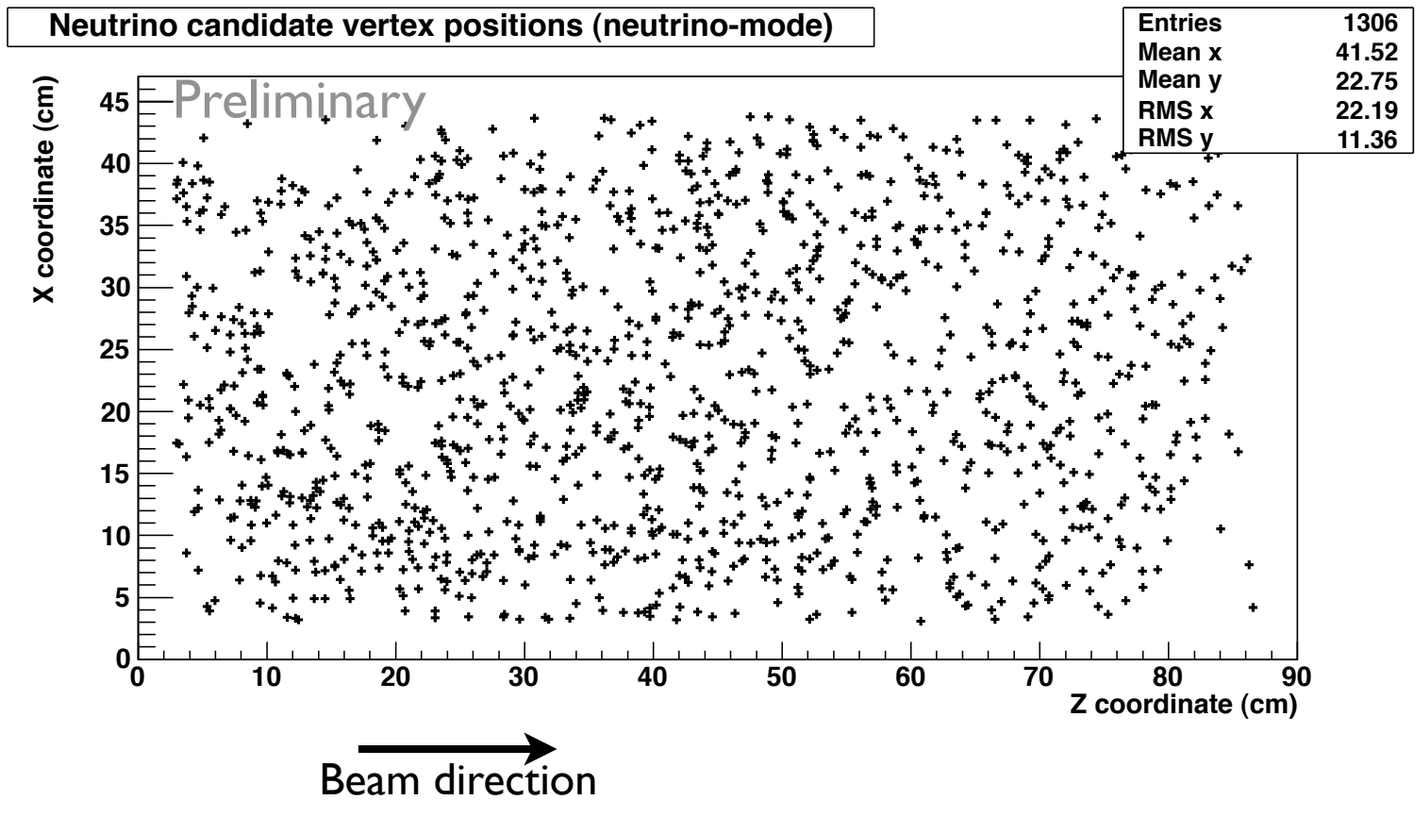
# ArgoNeuT analysis

- ArgoNeuT is currently analyzing the neutrino-mode data set, representing 2 weeks out of the 5 month total physics run.
- Neutrino and "maybe" neutrino events have been identified with a combination of software and human-based event scanning.

*Fiducial cuts have been applied




*Fiducial cuts have been applied

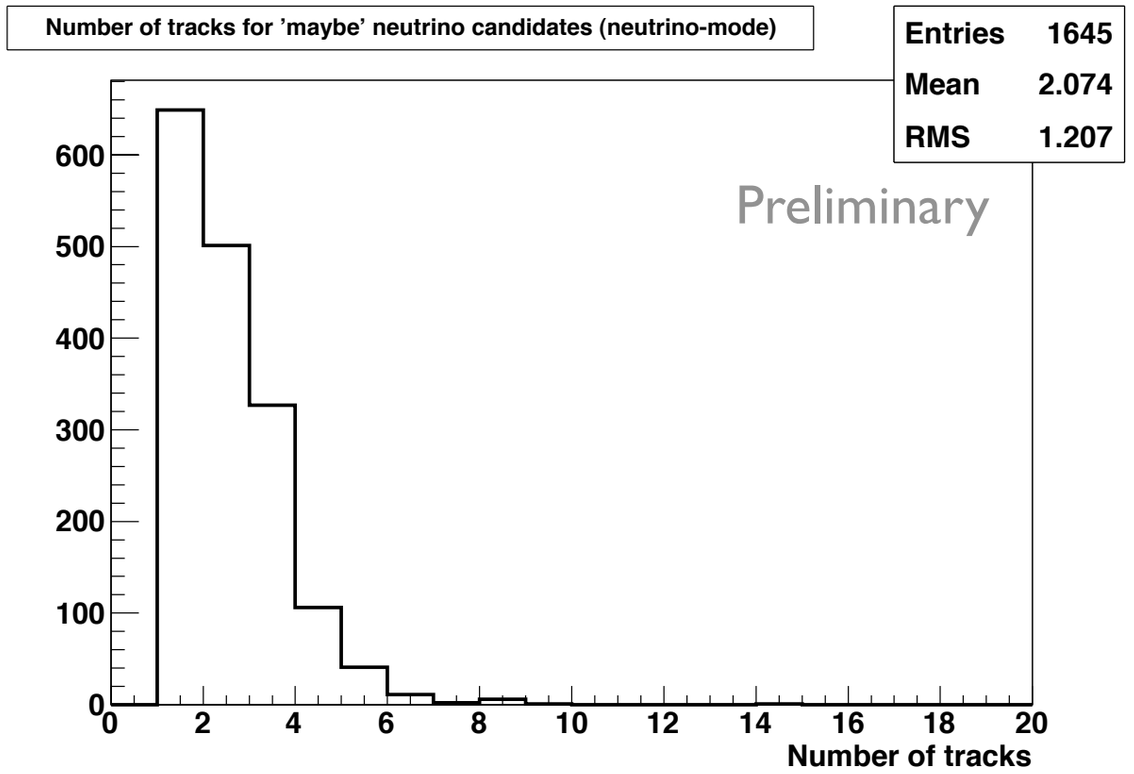


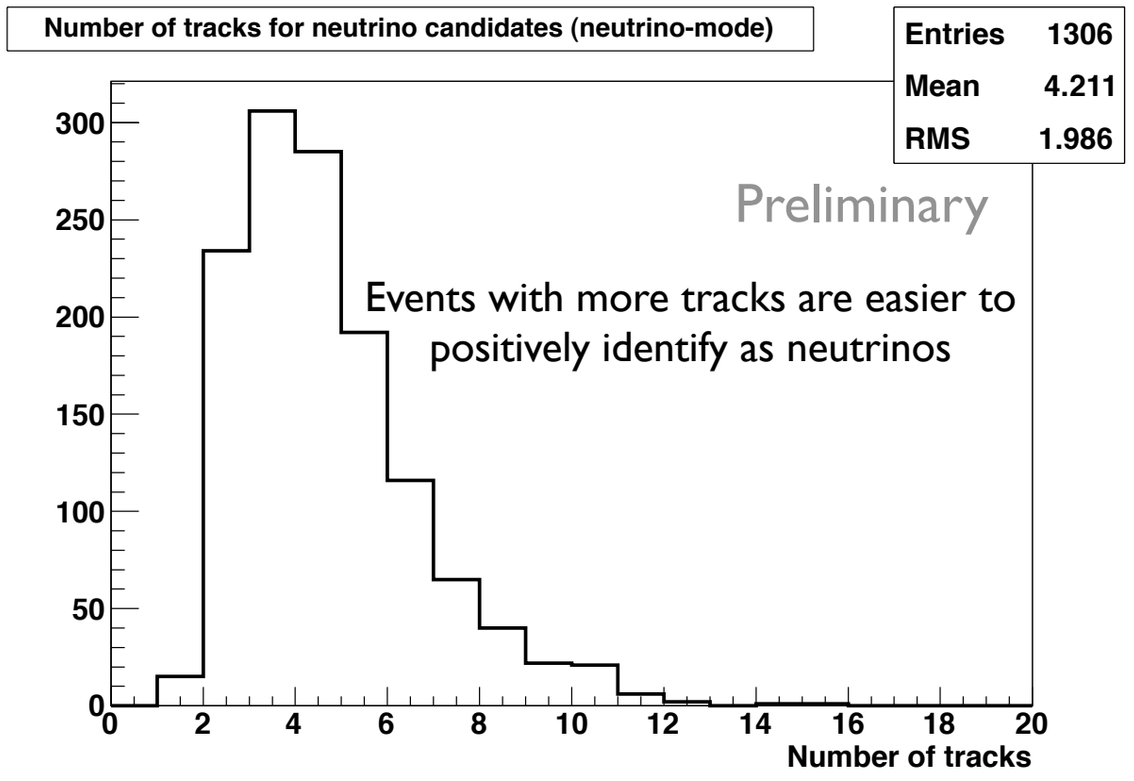
# ArgoNeuT analysis

- The number of tracks and showers in each neutrino-mode candidate event has also been determined.

| | Nuance channel | Reaction | #(nu mode)/0.1E20 POT |
|---|---|---|---|
| | n/a | $\nu_\mu$ CC | 1250 |
| | n/a | $\overline{\nu}_\mu$ CC | 104 |
| | n/a | $\nu_e$ CC | 25 |
| | n/a | $\nu_e$ CCQE | 2 |
| CCQE | 1 (CC) | $\nu_\mu n \longrightarrow \mu^- p$ | 206 |
| NCelastic | 2 (NC) | $\nu_\mu n \longrightarrow \nu_\mu n$ | 37 |
| | 2 (NC) | $\nu_\mu p \longrightarrow \nu_\mu p$ | 26 |
| Single pion resonant | 3 (CC) | $\nu_\mu p \longrightarrow \mu^- p\pi^+$ | 148 |
| | 4 (CC) | $\nu_\mu n \longrightarrow \mu^- p\pi^0$ | 88 |
| | 5 (CC) | $\nu_\mu n \longrightarrow \mu^- n\pi^+$ | 114 |
| | 6 (NC) | $\nu_\mu p \longrightarrow \nu_\mu p\pi^0$ | 30 |
| | 7 (NC) | $\nu_\mu p \longrightarrow \nu_\mu n\pi^+$ | 25 |
| | 8 (NC) | $\nu_\mu n \longrightarrow \nu_\mu n\pi^0$ | 37 |
| | 9 (NC) | $\nu_\mu n \longrightarrow \nu_\mu p\pi^-$ | 33 |
| DIS | 91 (CC) | $\nu_\mu N \longrightarrow \mu^- X$ | 545 |
| | 92 (NC) | $\nu_\mu N \longrightarrow \nu_\mu X$ | 176 |
| Coherent/diffractive | 96 (NC) | $\nu_\mu A \longrightarrow \nu_\mu A\pi^0$ | 13 |
| | 97 (CC) | $\nu_\mu A \longrightarrow \mu^- A\pi^+$ | 24 |

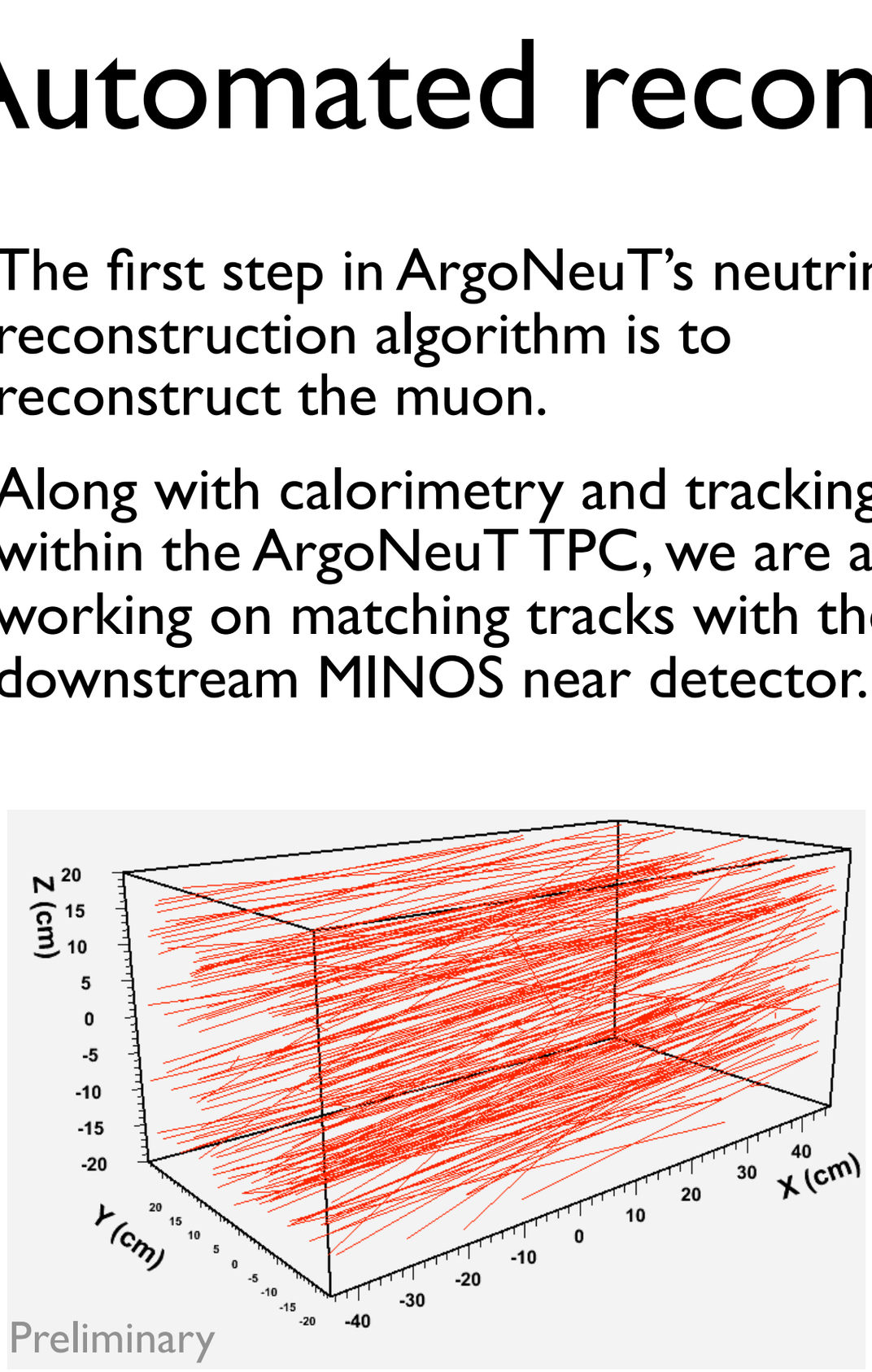
Neutrino-mode expected (Nuance MC) rates



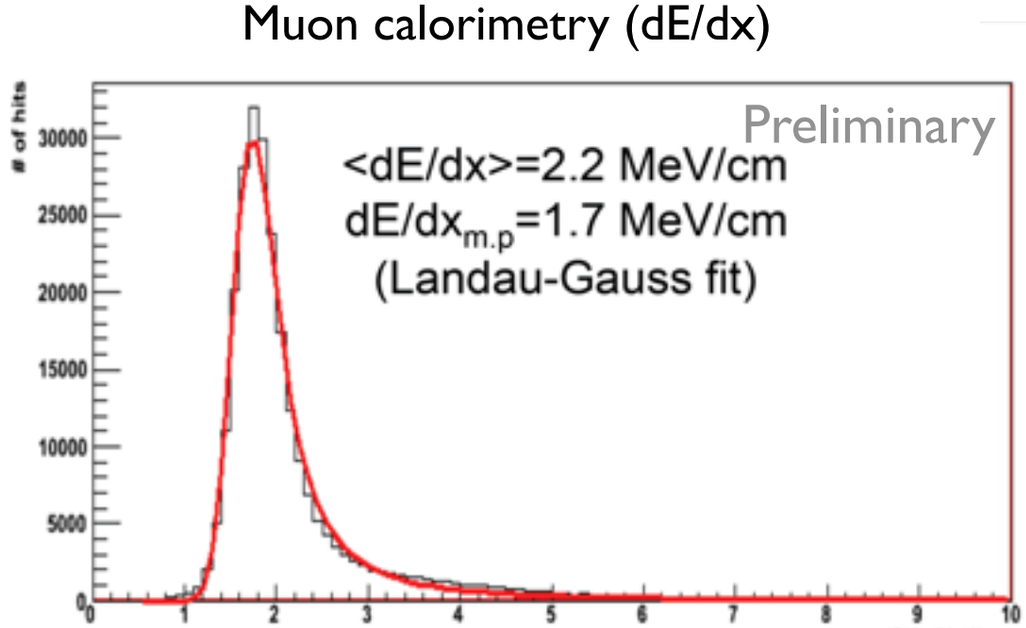



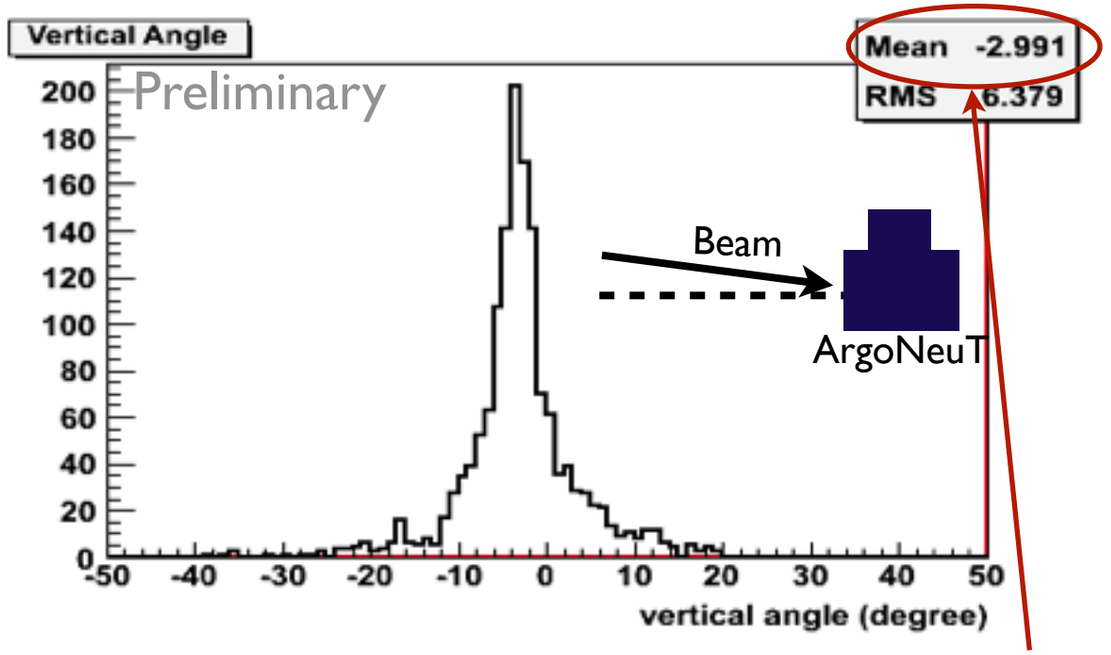
# Automated reconstruction of muons

- The first step in ArgoNeuT's neutrino reconstruction algorithm is to reconstruct the muon.
- Along with calorimetry and tracking within the ArgoNeuT TPC, we are also working on matching tracks with the downstream MINOS near detector.



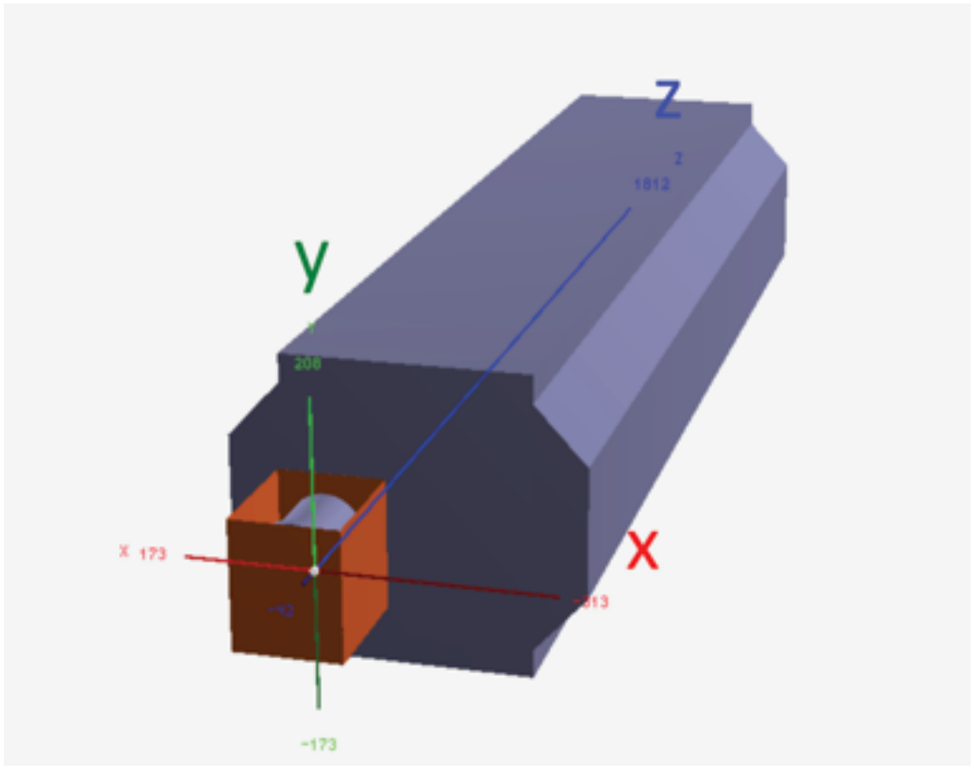

3D-reconstruction of muons



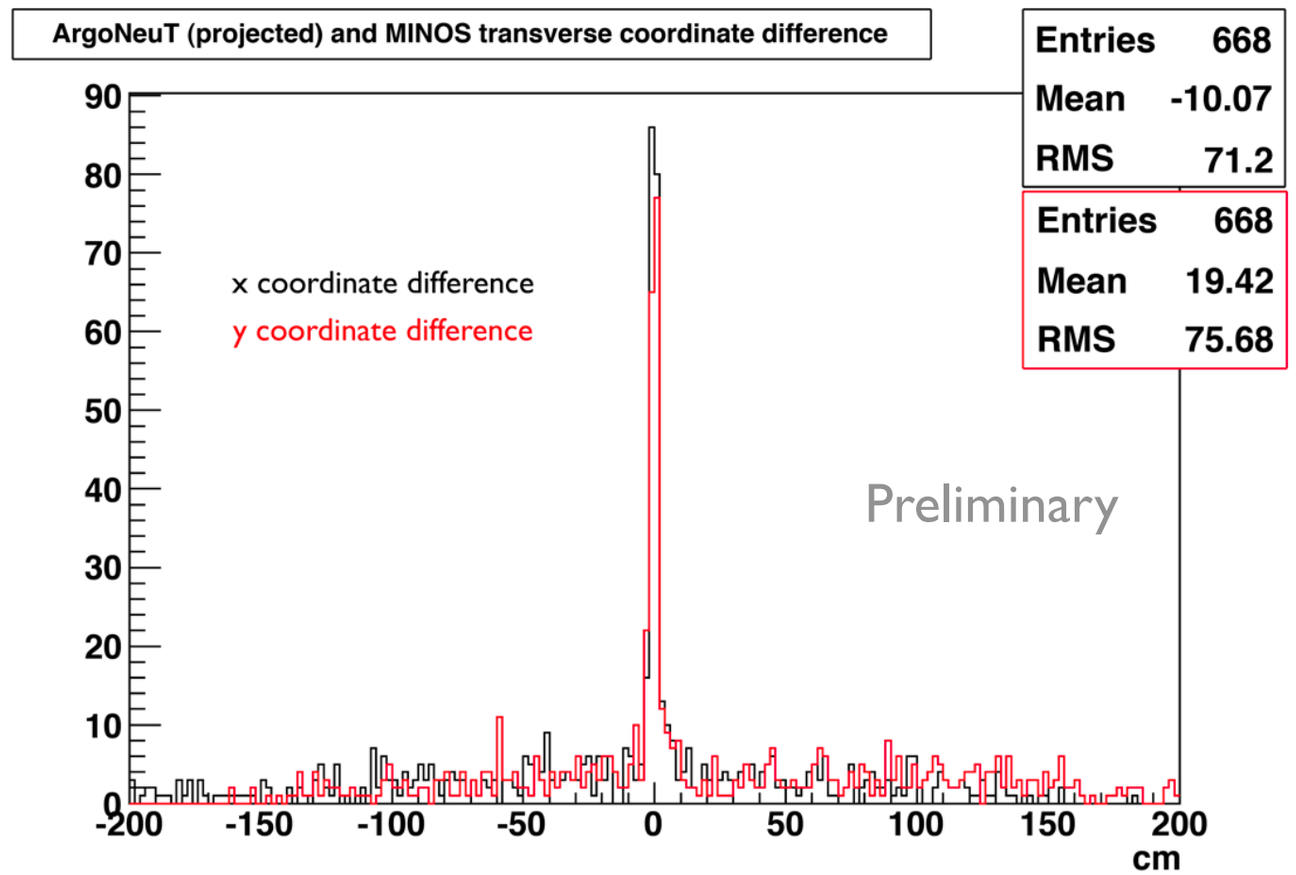




Angular distribution of muons (NuMI beam is at 3°)

# ArgoNeuT employs the downstream MINOS near detector to fully reconstruct muon sign and energy

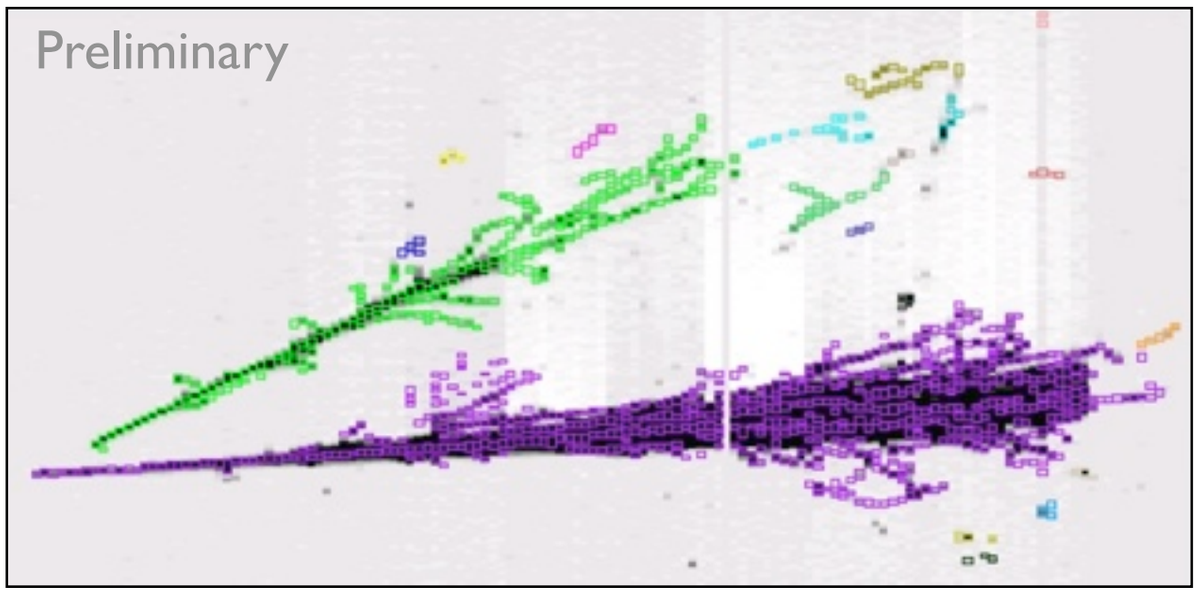



- The "lining up" of ArgoNeuT and MINOS has been accomplished with the use of neutrino-induced through-going muons.

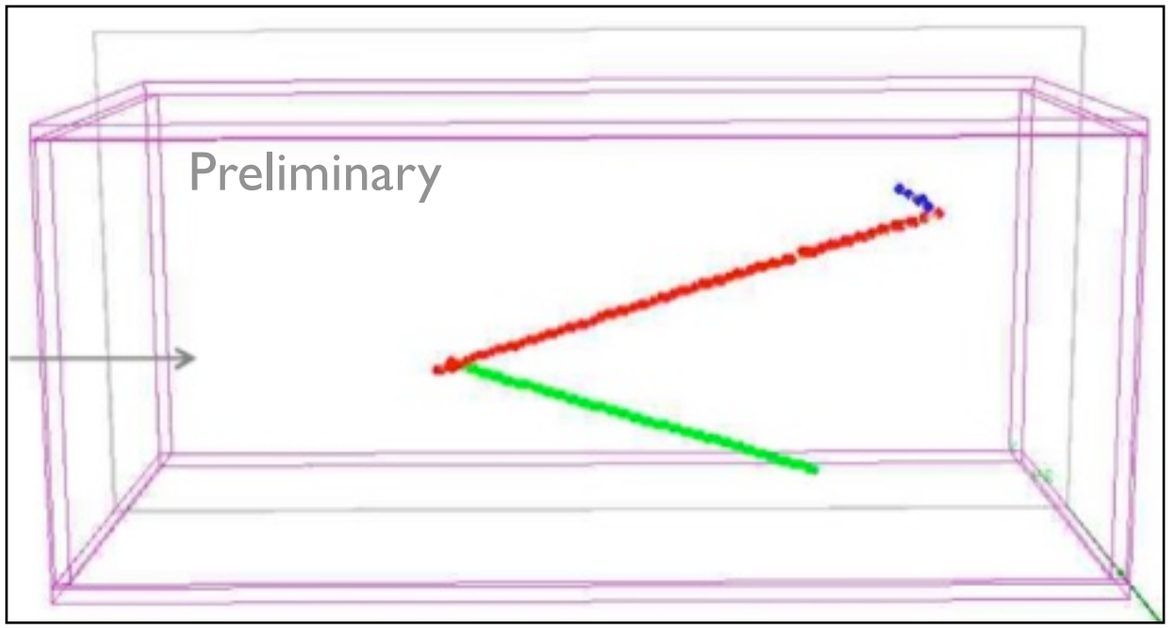


# Reconstructing neutrino events

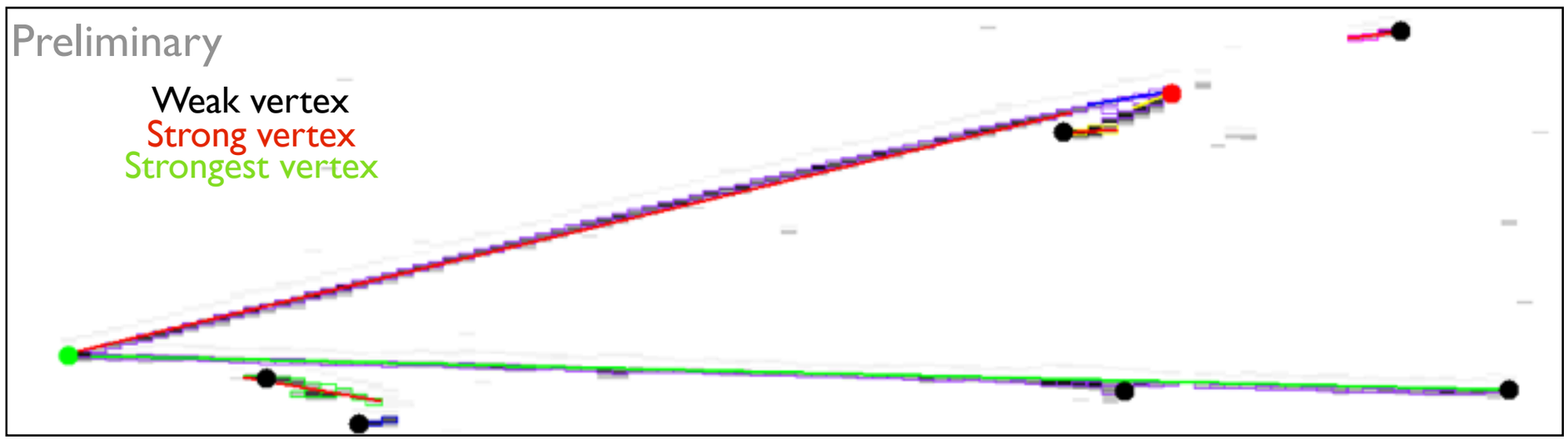
- ArgoNeuT has created an automated reconstruction framework currently capable of hit finding, calorimetry, cluster/line/vertex-finding, track fitting and 3D track matching.




Hit finding + density-based clustering.



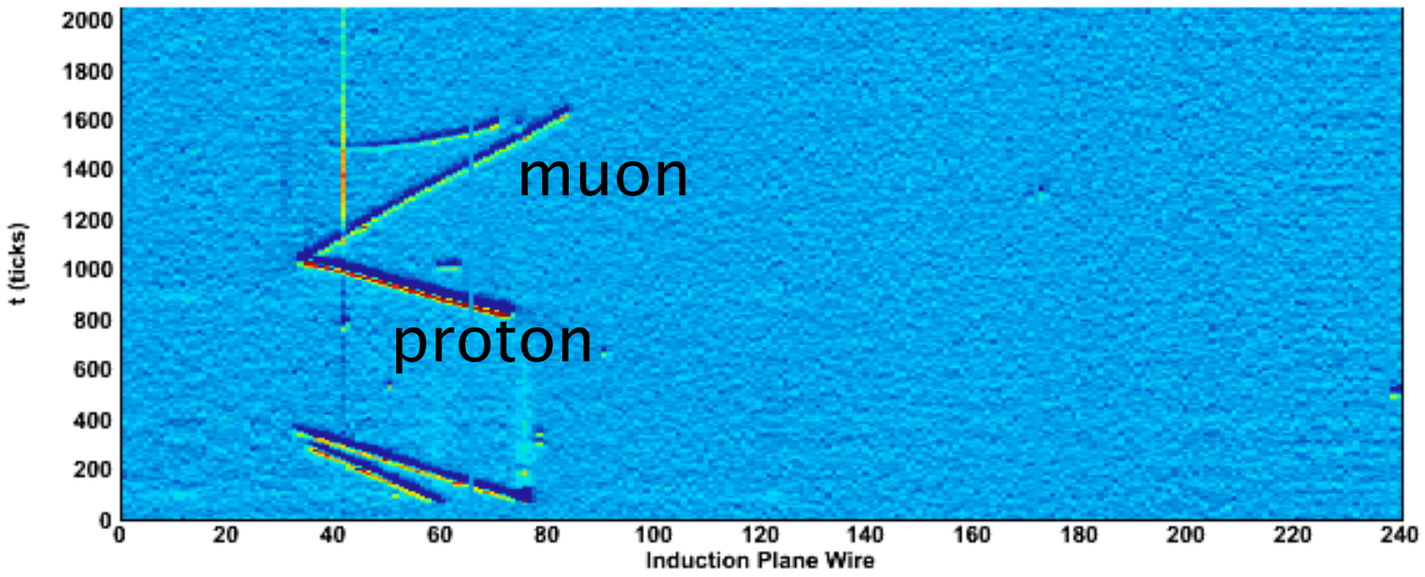

3D reconstruction

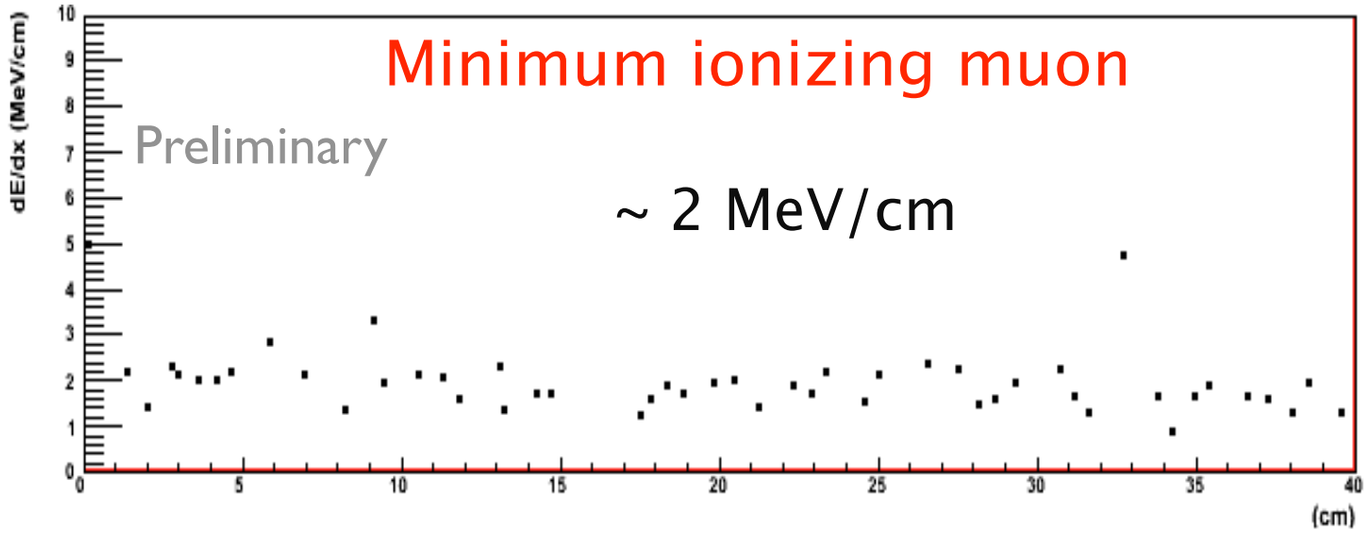



Line finding/fitting + vertex/endpoint finding

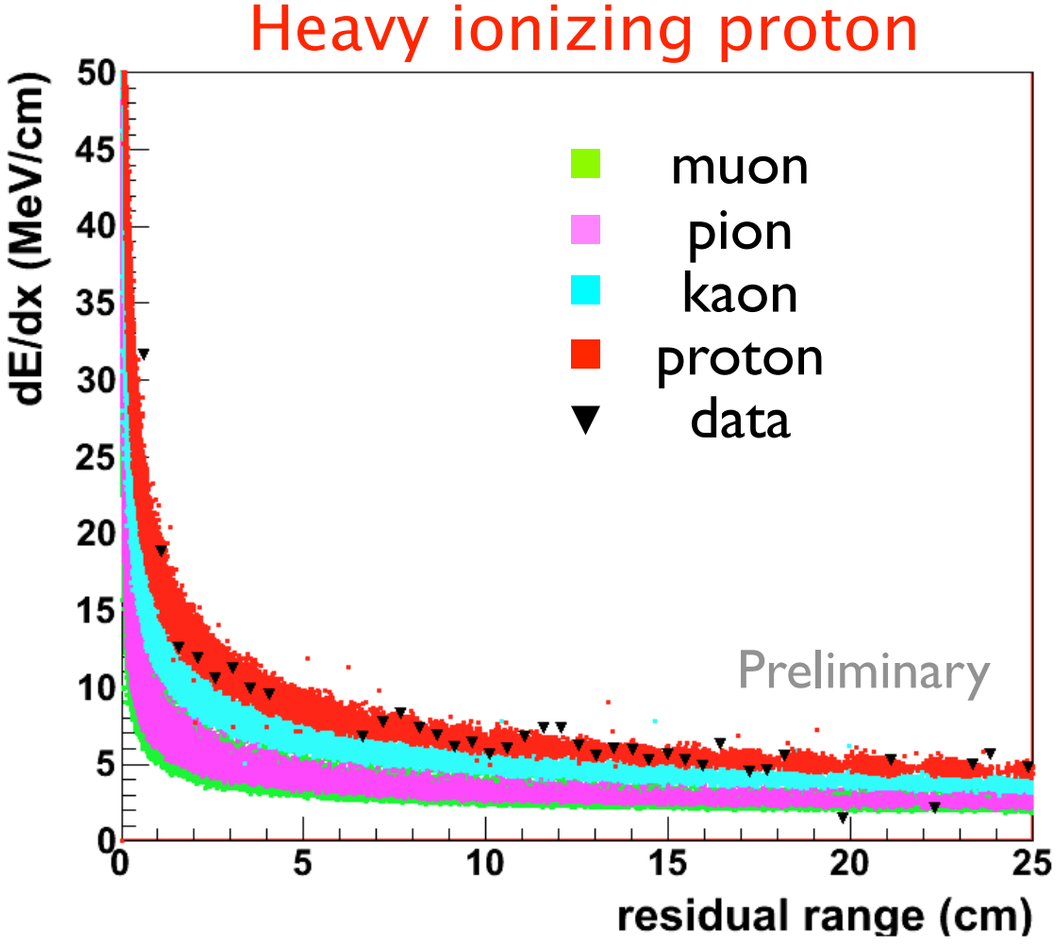
# Calorimetry

- dE/dx is vital to tagging the muon and proton(s) in CCQE-like events




A CCQE-like event's proton and muon dE/dx reconstructed

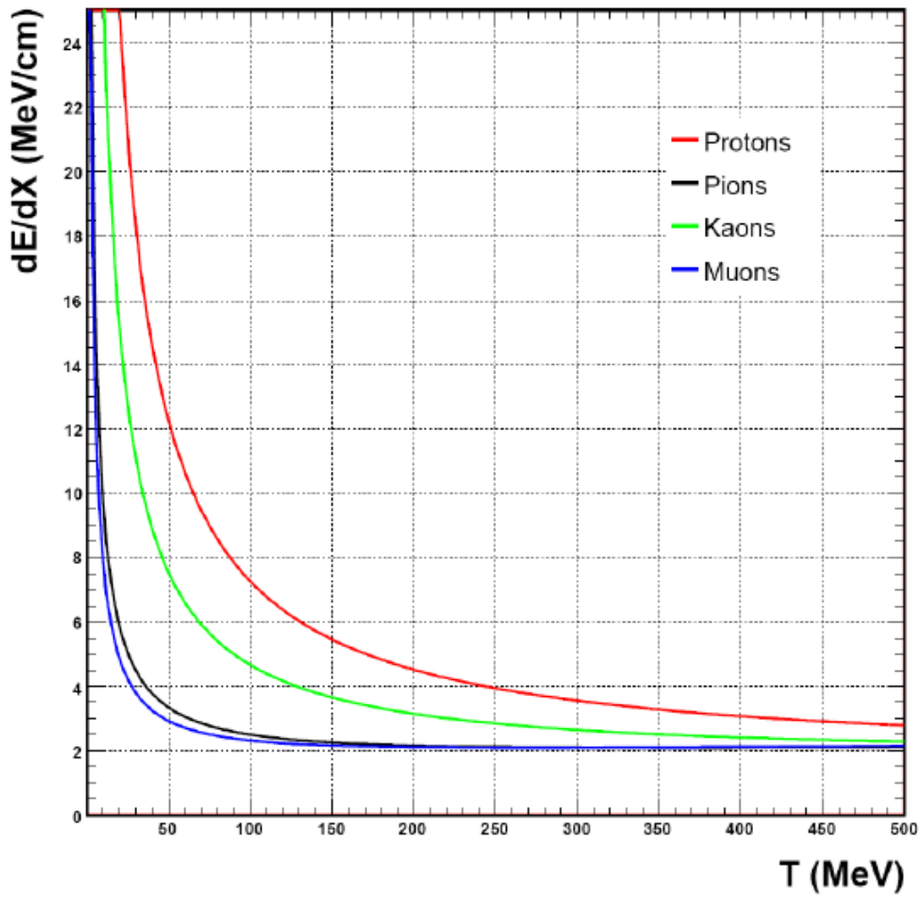


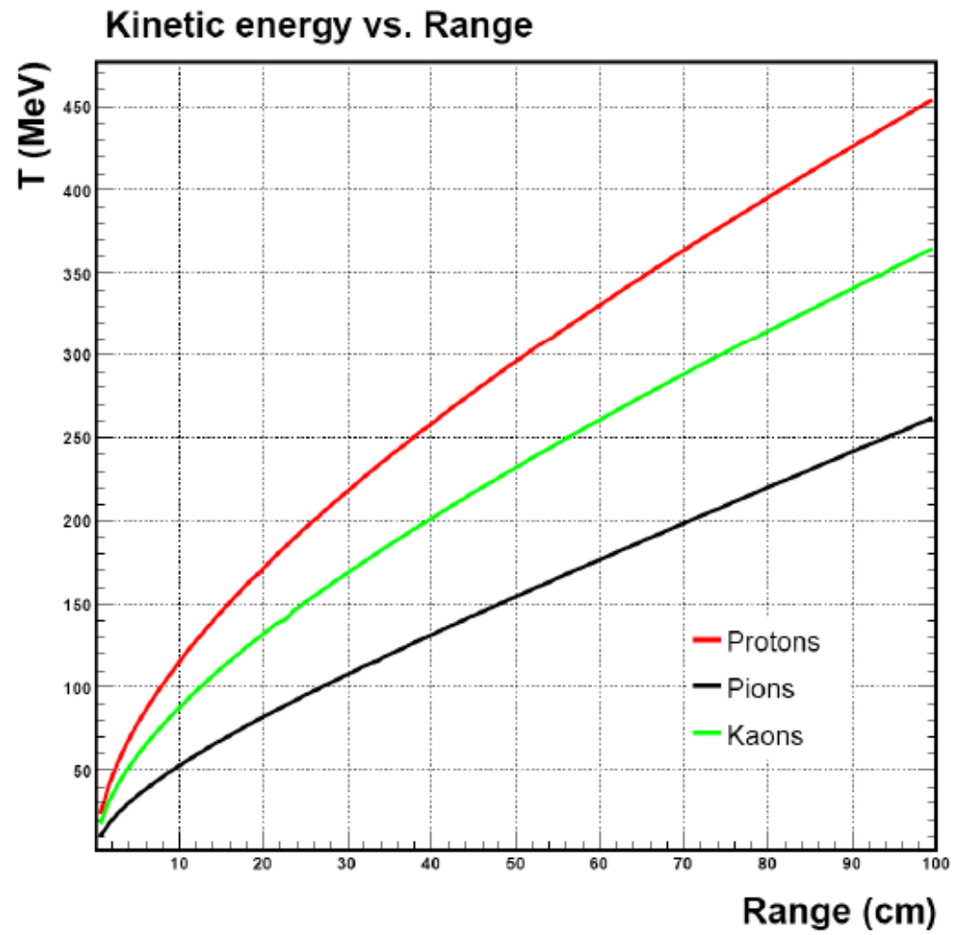
# Conclusions

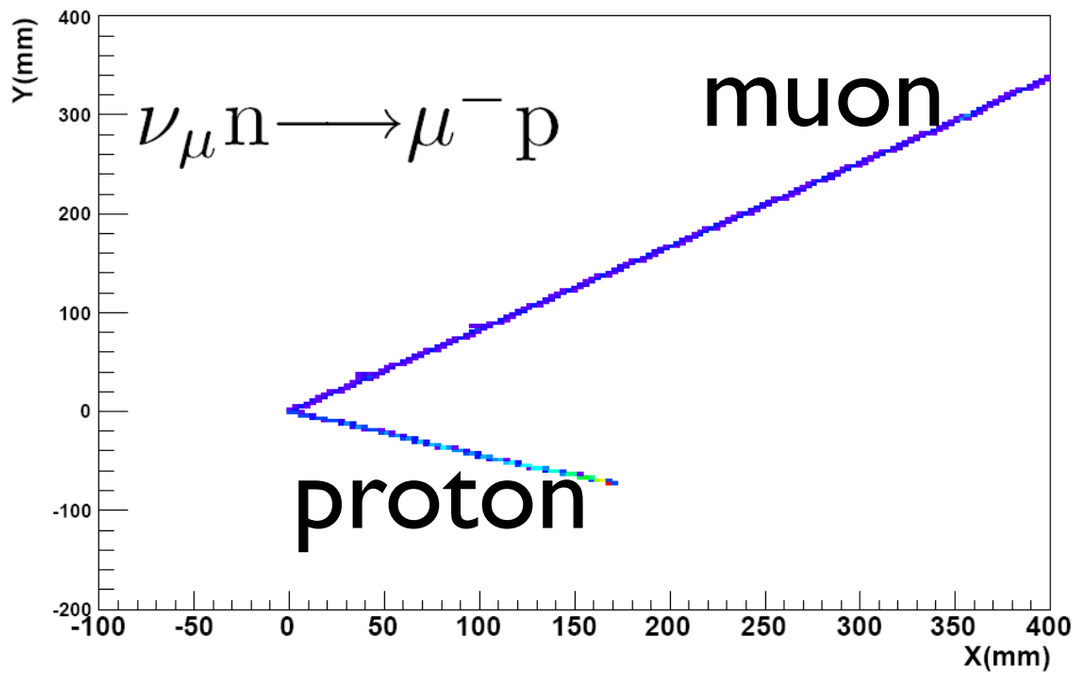
- ArgoNeuT had a very successful >5 month long physics run in the NuMI beamline. The experiment collected the first 1,000s of (anti-) neutrino events ever with a LArTPC in a low-energy neutrino beam.
- We are hard at work analyzing the neutrino-mode data set.
- First ArgoNeuT results appearing in Spring/Summer 2011.
  - Muon reconstruction.
  - CCQE-like differential cross section and vertex activity analyses.

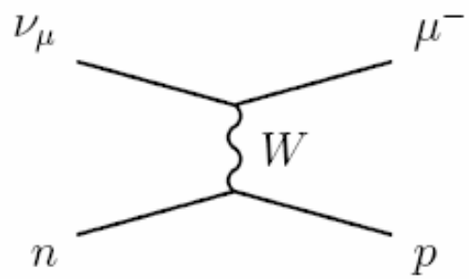
# Backup slides

# dE/dx, kinetic energy, and range

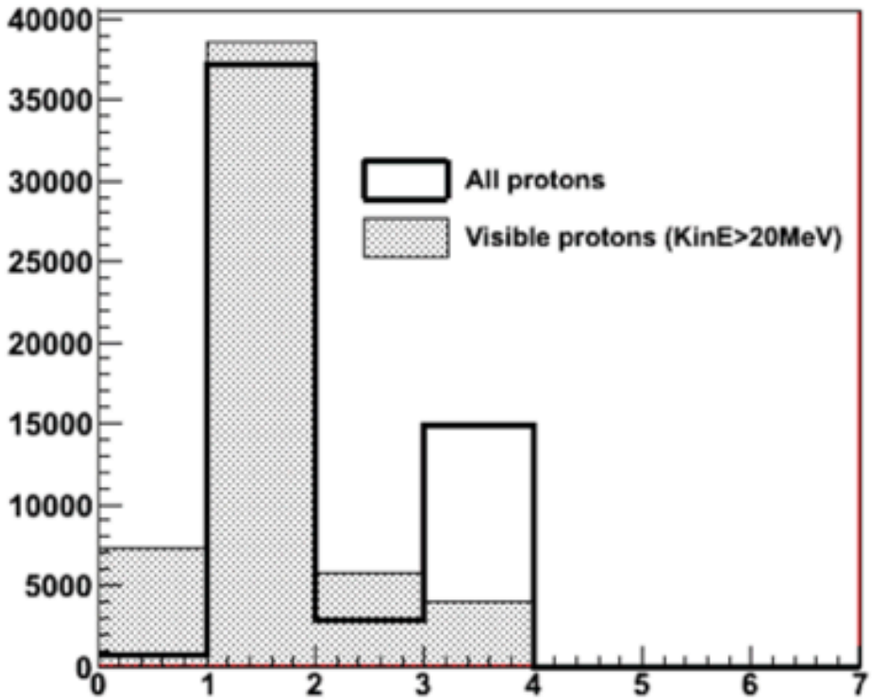


# MonteCarlo Simulation *CC QE sample - LE $\nu_\mu$ on $^{40}Ar$*



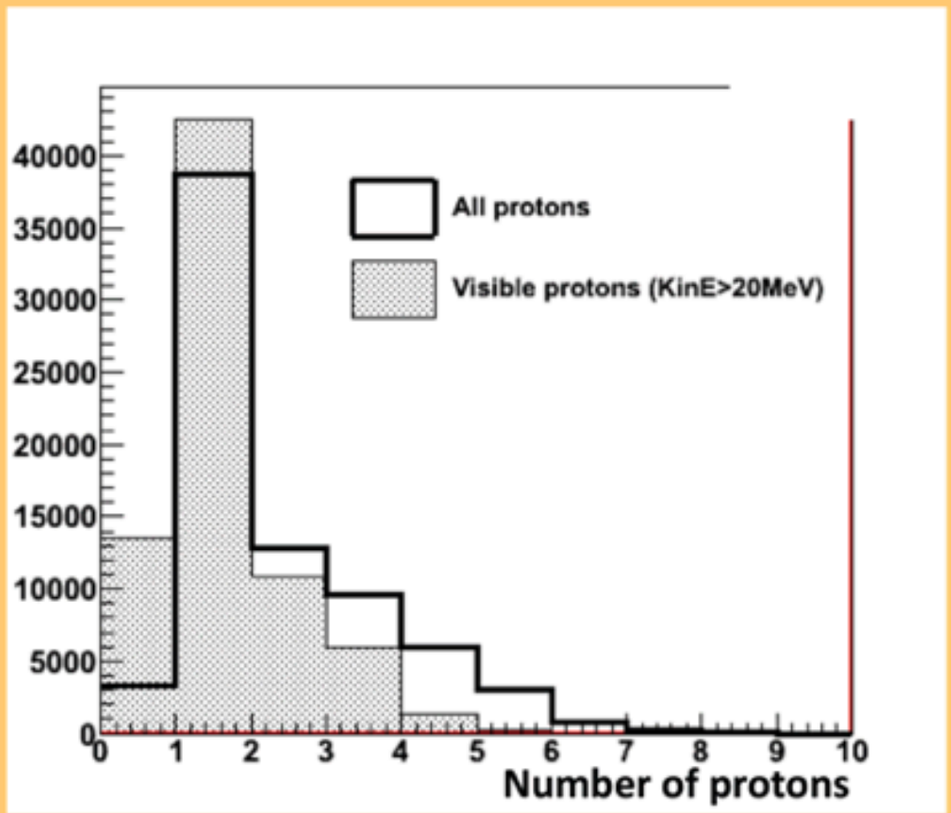

Visible proton: $T_p \geq 20$ MeV (87%)

| | | |
|---|---|---|
| 0p | → | 13% |
| 1p | → | 70% |
| 2p | → | 10% |
| 3p | → | 7% |

Neutrons:

| | | |
|---|---|---|
| 0 n | → | 60% |
| 1 n | → | 10% |
| 2 n | → | 30% |

GENIE




Visible proton: $T_p \geq 20$ MeV (82%)

| | | |
|---|---|---|
| 0p | → | 19% |
| 1p | → | 57% |
| 2p | → | 14% |
| 3p | → | 8% |
| 4p | → | 2% |

Neutrons:

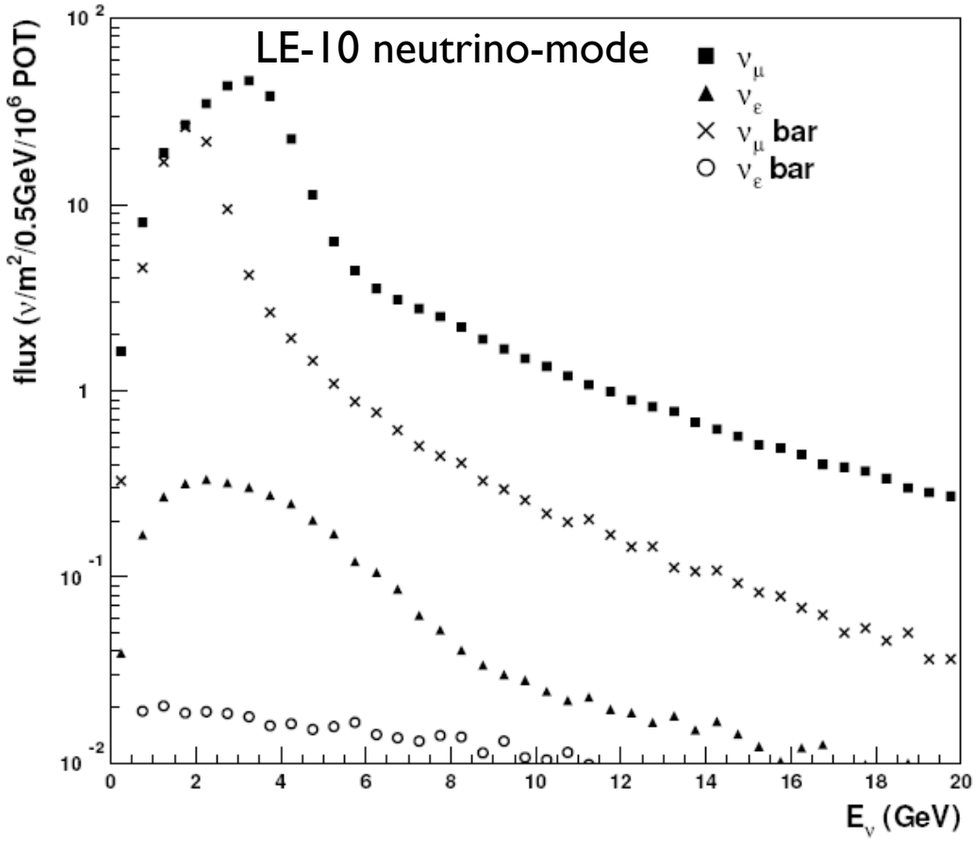
| | | |
|---|---|---|
| 0 n | → | 14% |
| 1 n | → | 37% |
| 2 n | → | 15% |
| 3 n | → | 13% |
| 4 n | → | 9% |
| 5 n | → | 8% |
| 6 n | → | 3% |
| 7 n | → | 1% |

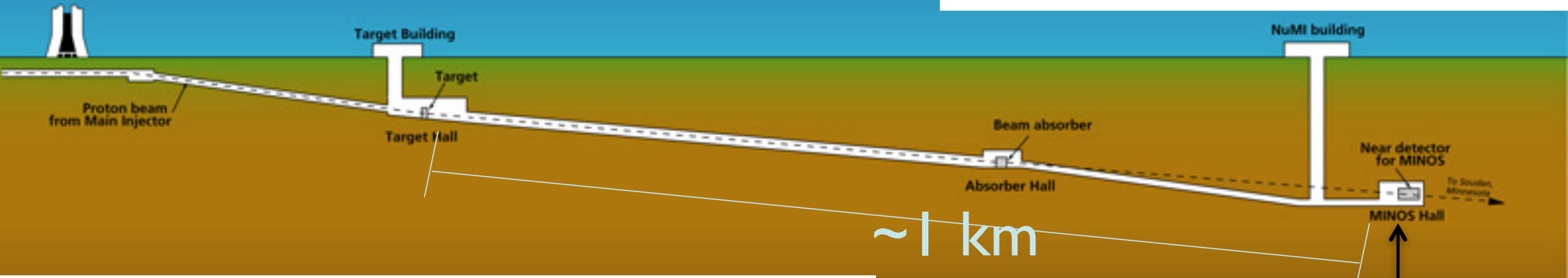
FLUKA

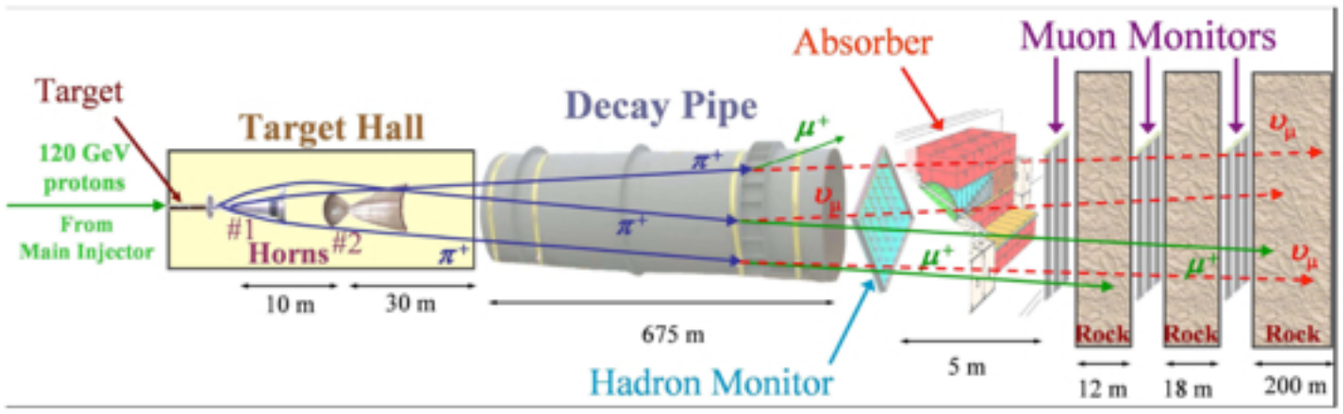
Also γ and α are frequently produced and give detectable signals

ArgoNeuT will greatly improve the world's knowledge of FSI and inform generators like GENIE and FLUKA.

# NuMI Tunnel Project

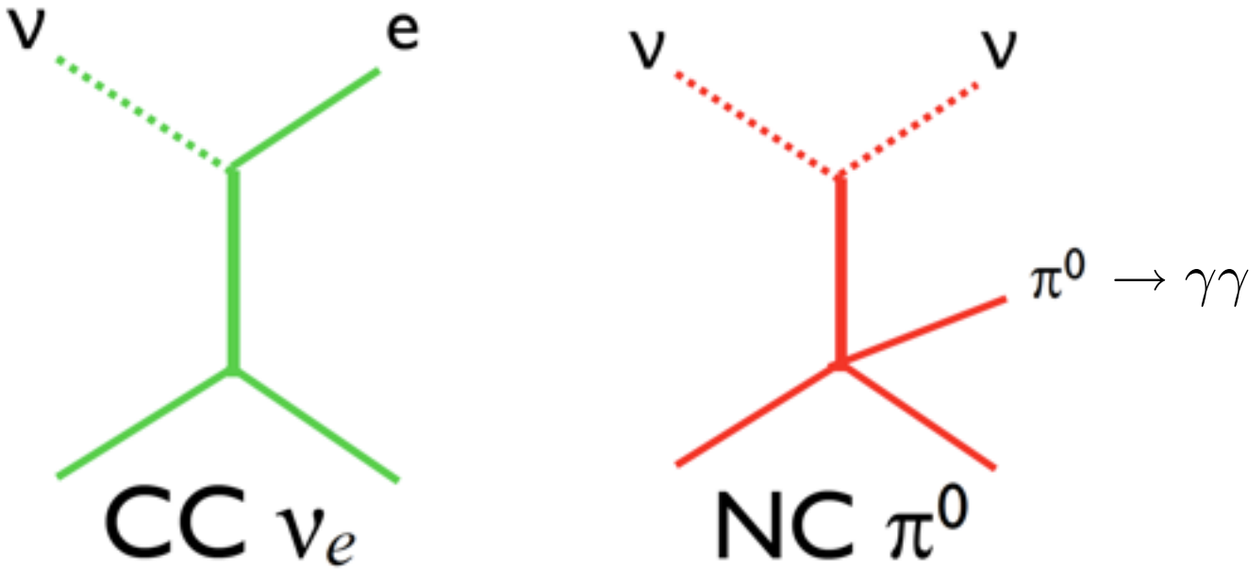


# Signal and background

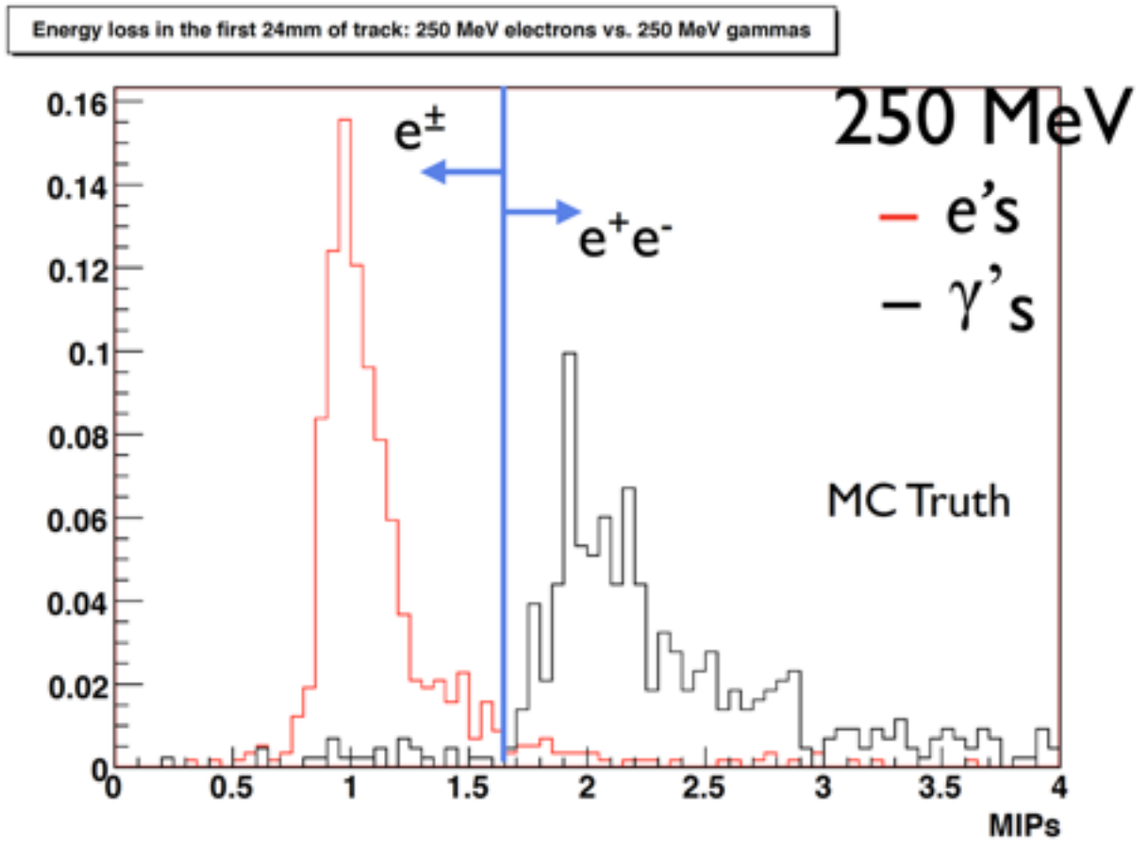
- NC$\pi^0$ events represent the largest background for $\nu_e$ appearance searches.
- LArTPCs offer 3D imaging and dE/dx to reduce the background to nearly zero.




**Mis-ID of an NCPi0 event (w/o dE/dx):**

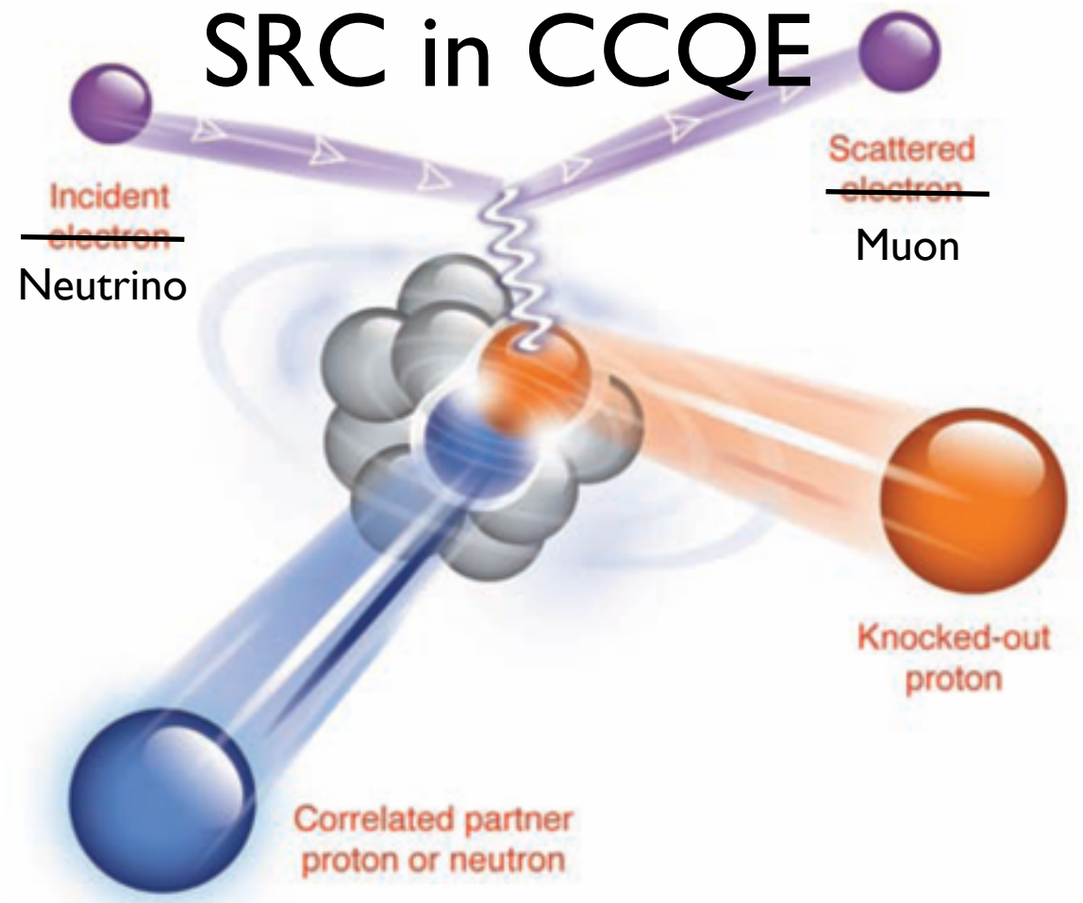
- One gamma converts outside detector
- Two gammas appear to be one track
- One gamma is absorbed by photo-nuclear interaction
- A gamma converts close to event vertex

A LArTPC solves all of these issues at once!




dE/dx for electrons and gammas in first 2.4 cm of track

# SRC in neutrino interactions




Majority (~90%) of pairs are n-p. ~20% of nucleons are paired in Ar

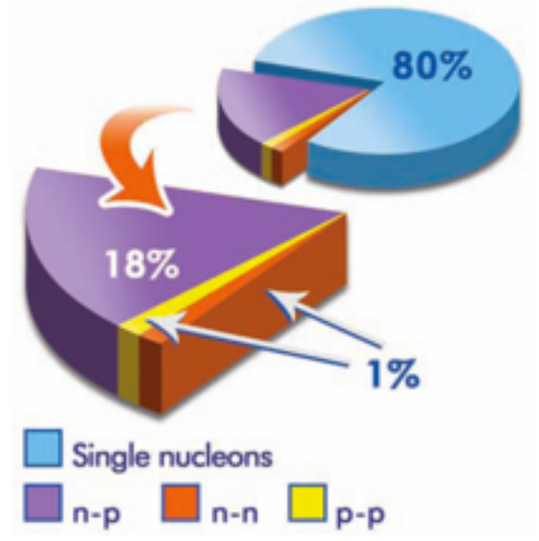



**Fig. 3.** The average fraction of nucleons in the various initial-state configurations of $^{12}C$.

**Fig. 1.** Illustration of the $\nu_\mu n \to \mu^- pp$ reaction. The incident neutrino beam couples to a nucleon-nucleon pair via a virtual boson In the final state, the scattered muon is detected along with the two nucleons that are ejected from the nucleus. Typical nuclear density is about 0.16 nucleons/fm$^3$, whereas for pairs the local density is approximately five times larger.

$$\nu_\mu n \longrightarrow \mu^- pp$$

- This is one of the hottest topics in nuclear physics today! It was the "featured topic" at this year's APS Division of Nuclear Physics conference.
- SRC is unobserved in neutrino interactions!

# NOMAD and MiniBooNE vertex activity

NOMAD does consider nucleons in their CCQE cross section analysis. However, their energy threshold for proton reconstruction is ~300 MeV.

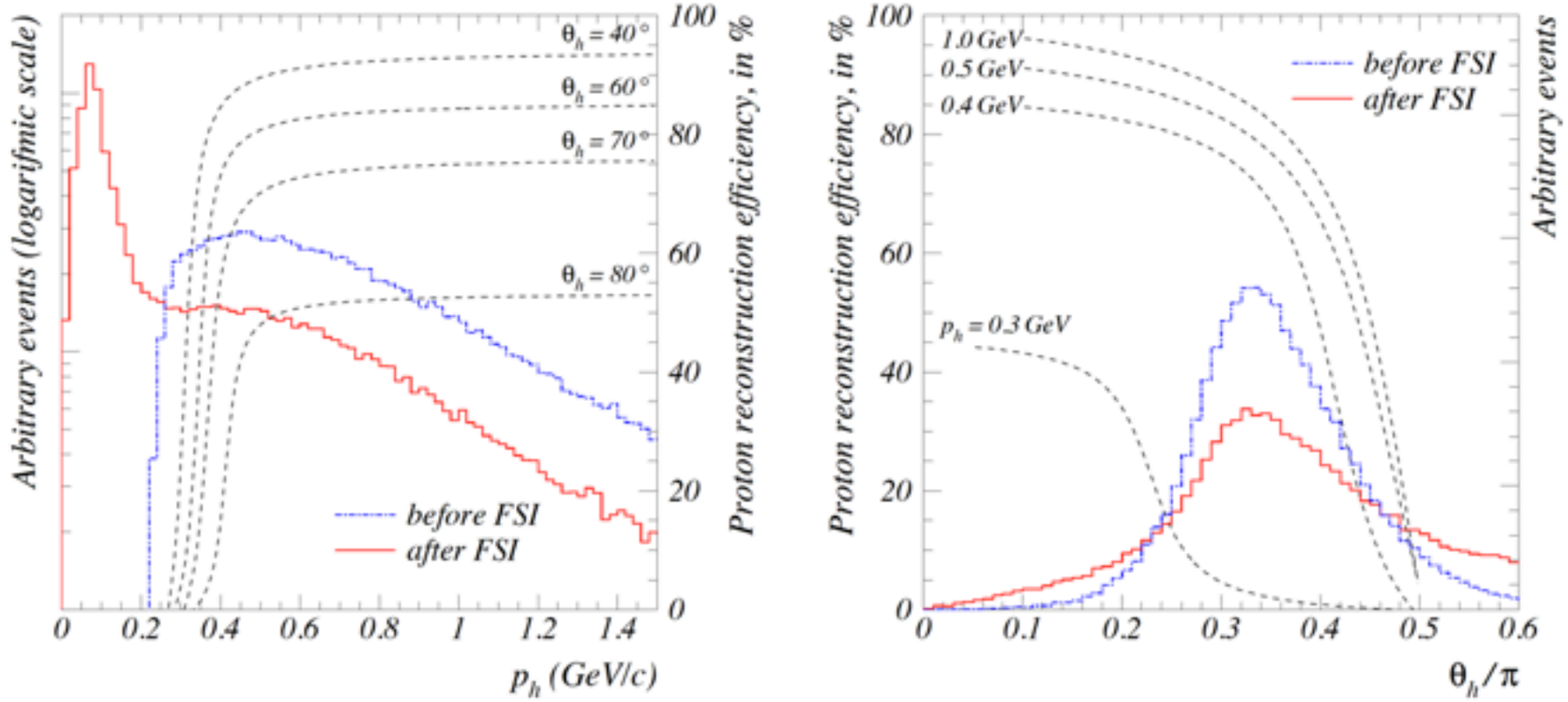



**Fig. 6.** Distribution of the leading proton momentum (left) and emission angle (right) before (dash-dotted line) and after (solid line) FSI simulation. Dashed lines show the proton reconstruction efficiency as function of the proton momentum and emission angle (for $\pi < \varphi_h < 2\pi$).

- MiniBooNE does not consider nucleons in their CCQE cross section analysis.

# What does SRC evidence look like?

- Backward going protons, which are quite unlikely only considering kinematic phase space.
- High momentum protons.
- (n protons in neutrino CCQE-like)-(n protons in anti-neutrino CCQE-like)>1 (after accounting for FSI)
- In general: vertex activity differences between neutrino and anti-neutrino.

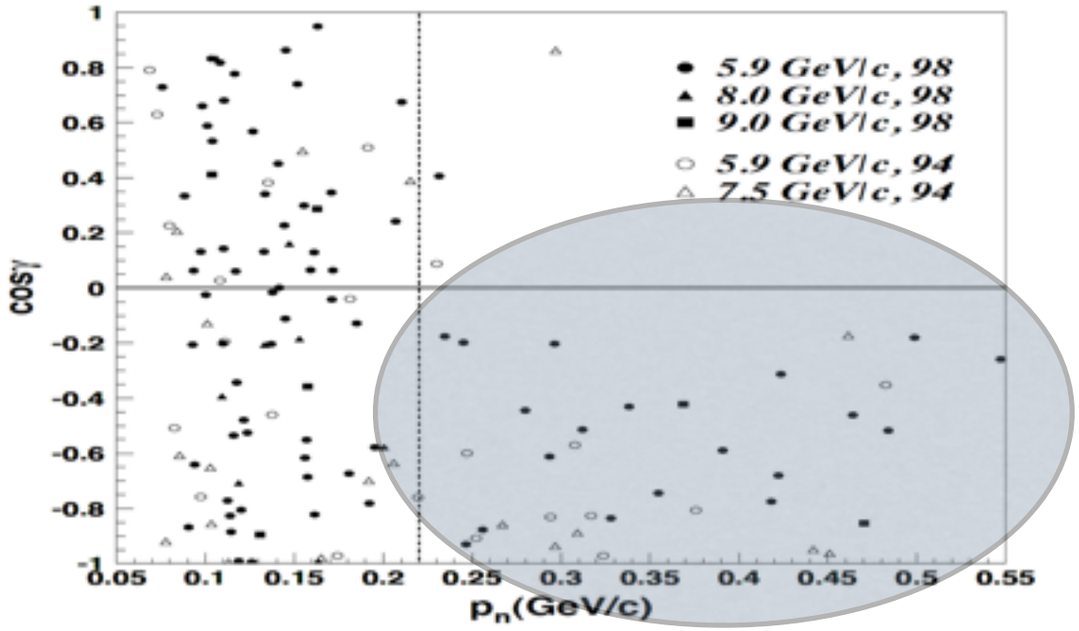



FIG. 1: The correlation between $p_n$ and its direction $\gamma$ relative to $\vec{p}_2$. Data labeled by 94 and 98 are from Ref.[6] and [7] respectively. The momenta are the beam momenta. The dotted vertical line corresponds to $k_F = 220$ MeV/c.